MMOD Risk/External Inspection Needs for Re-entry TPS

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NASA Johnson Space Center

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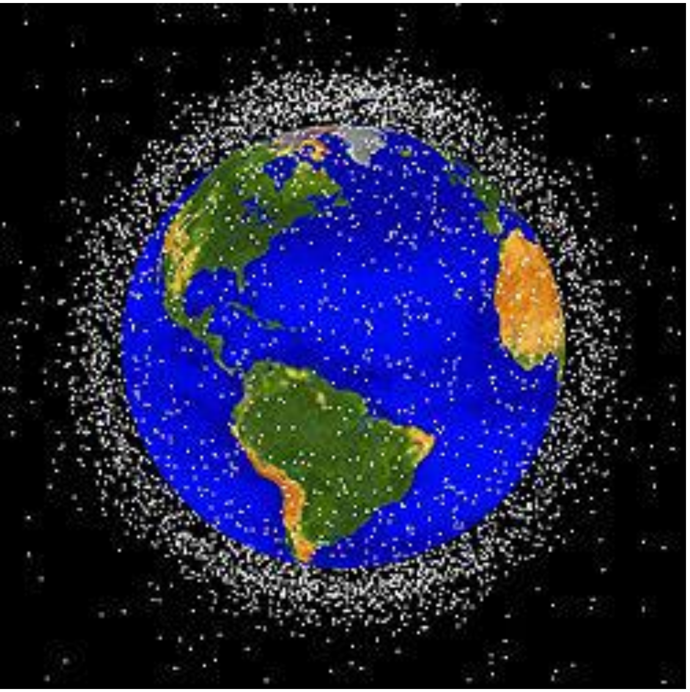
Purpose of this presentation

- Provide background on micro-meteoroid & orbital debris (MMOD) environment and risk
- Describe external inspection needs for re-entry TPS

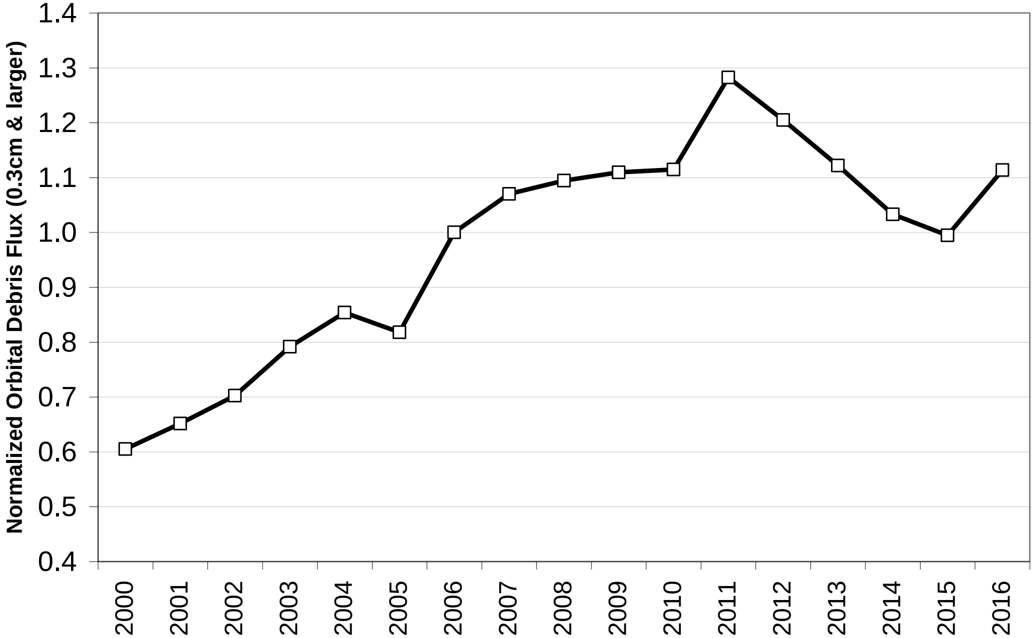
MMOD Environment Models

- Orbital Debris (OD) environment models
  - Orbital Debris environment (ORDEM2000): 1-17 km/s
    - Debris flux increases with increasing altitude up to about 1500km altitude
    - Debris is not a major factor above GEO altitude (35786km)
  - Debris environment subject to change (ORDEM 3.0 release pending)

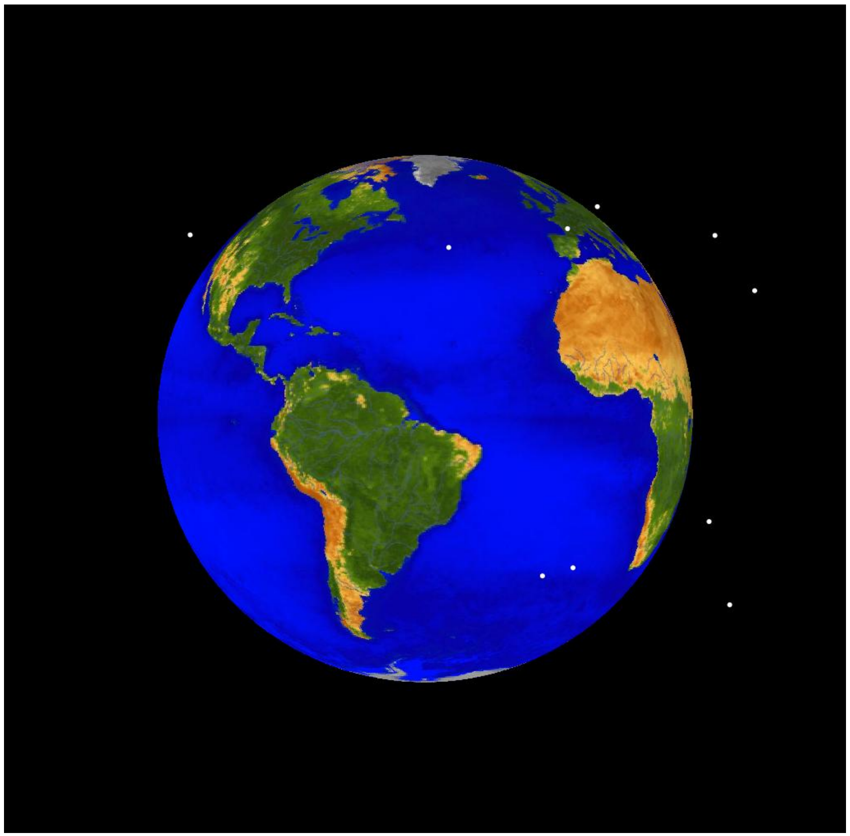
Orbital Debris in Earth Orbit

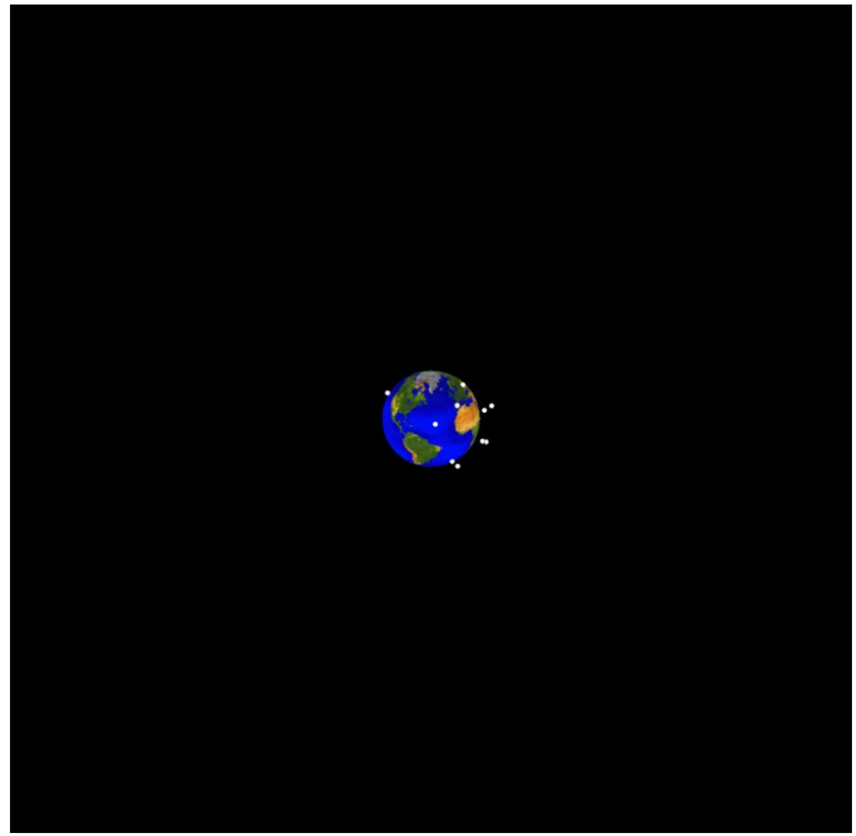


Normalized Orbital Debris Flux by Year at ISS Altitude For Threat Particle Sizes > 0.3cm
(Normalized to 2006 flux)
Note OD Risk is proportional to Flux



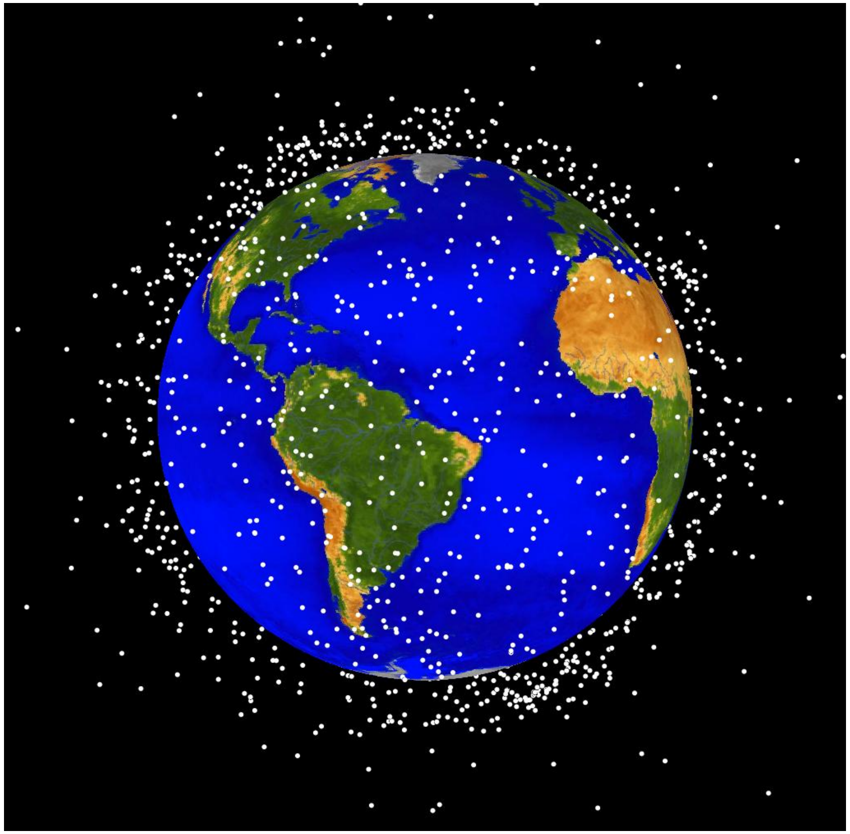
1960

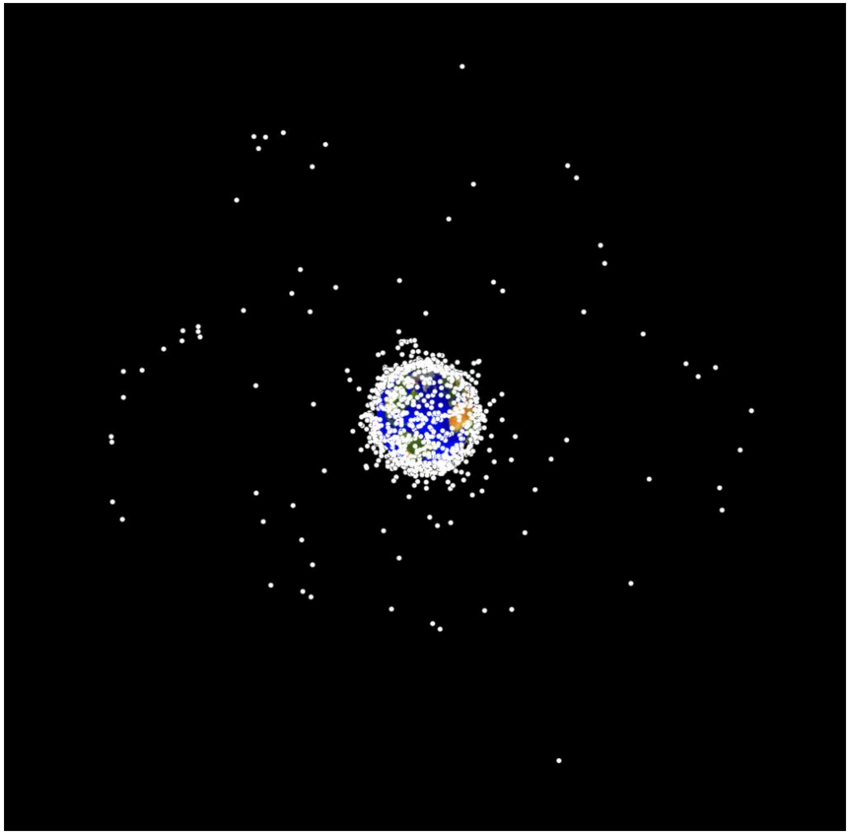




Cataloged objects >10 cm diameter

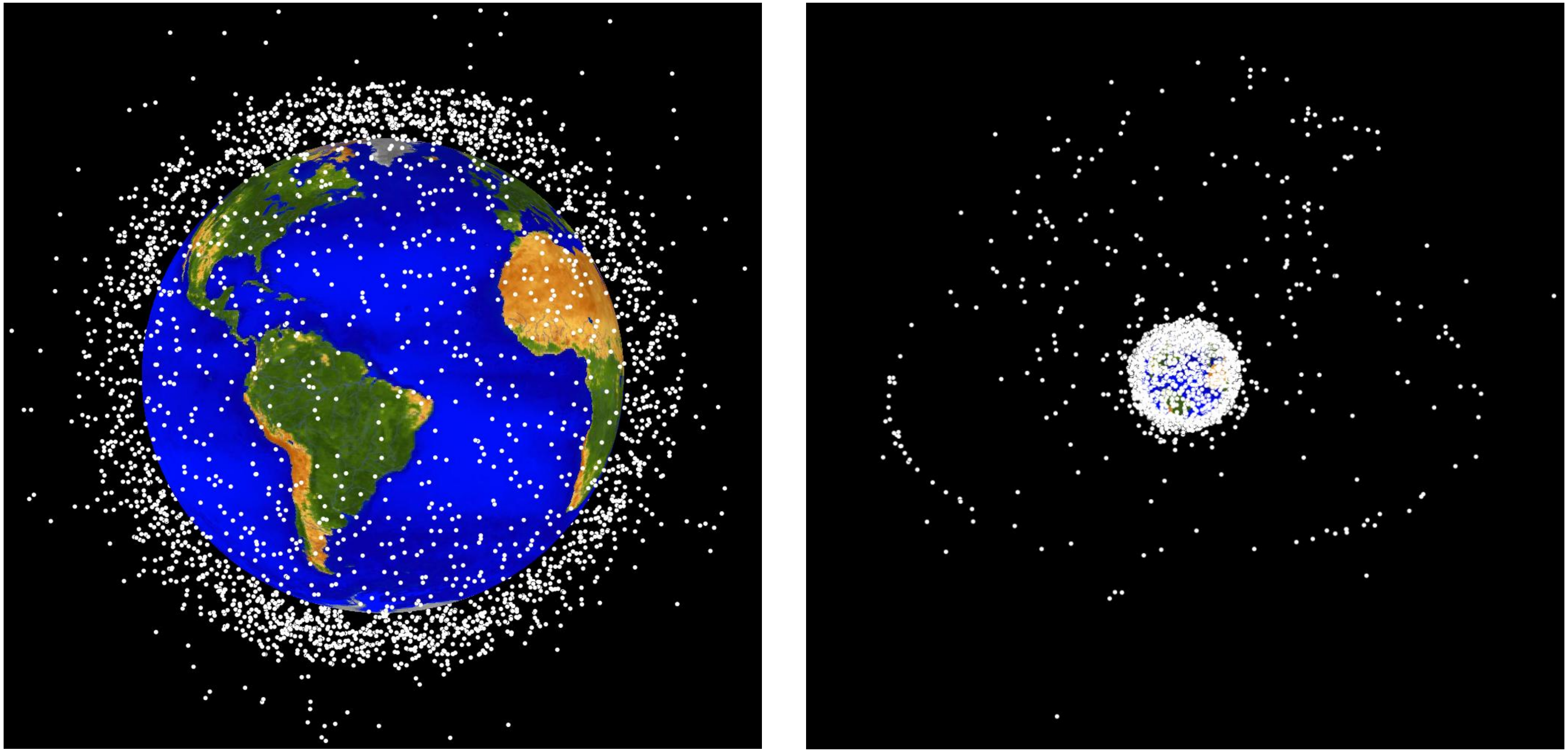
1970





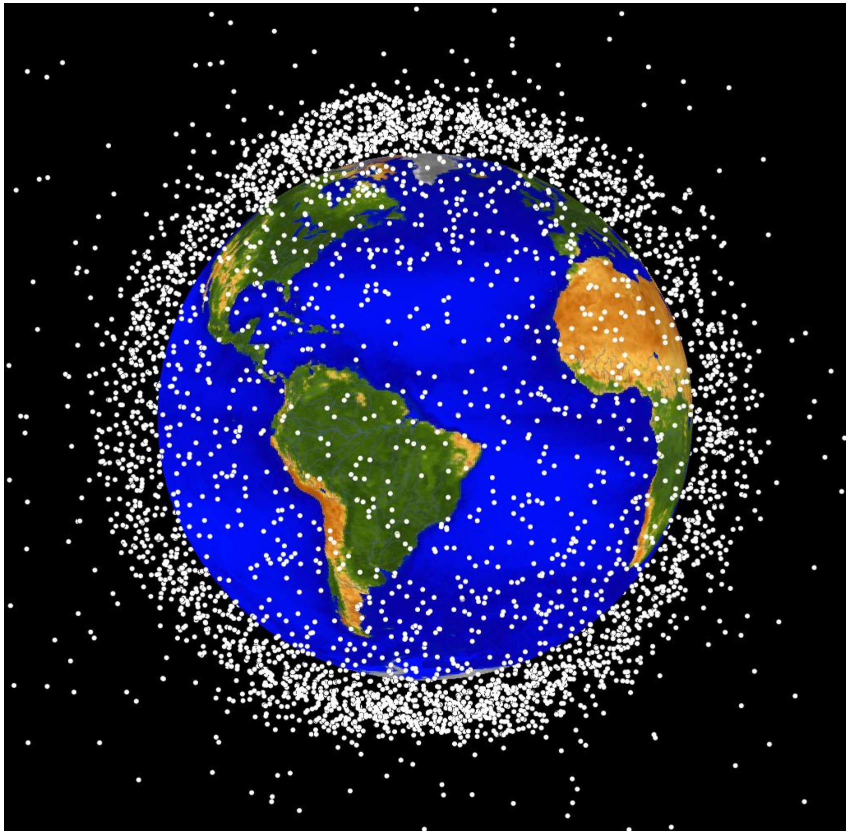
Cataloged objects >10 cm diameter

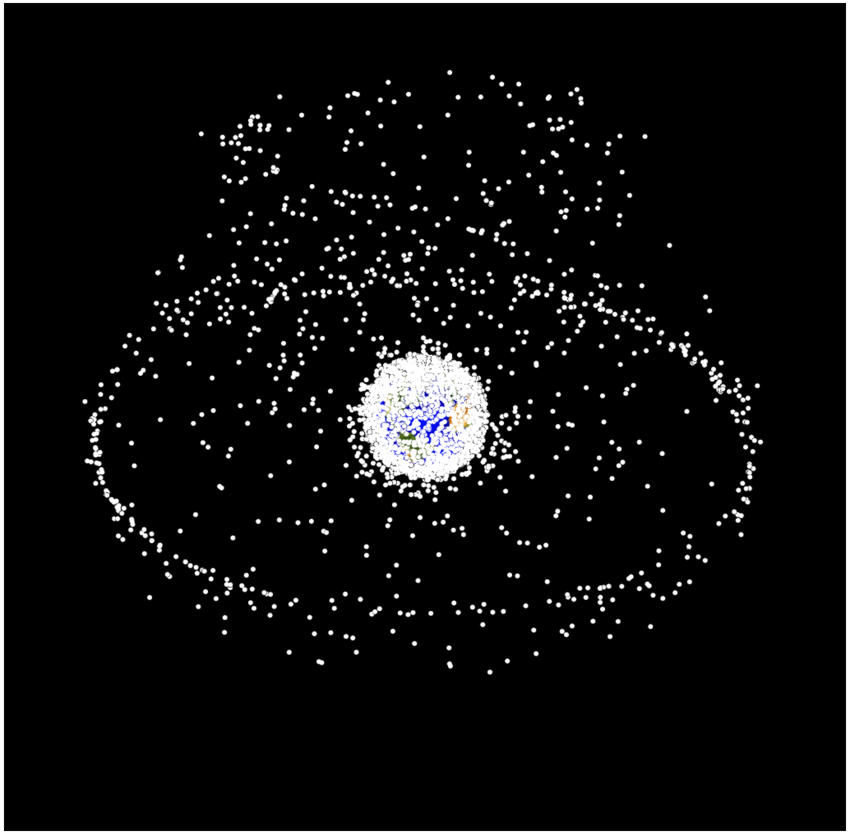
1980



Cataloged objects >10 cm diameter

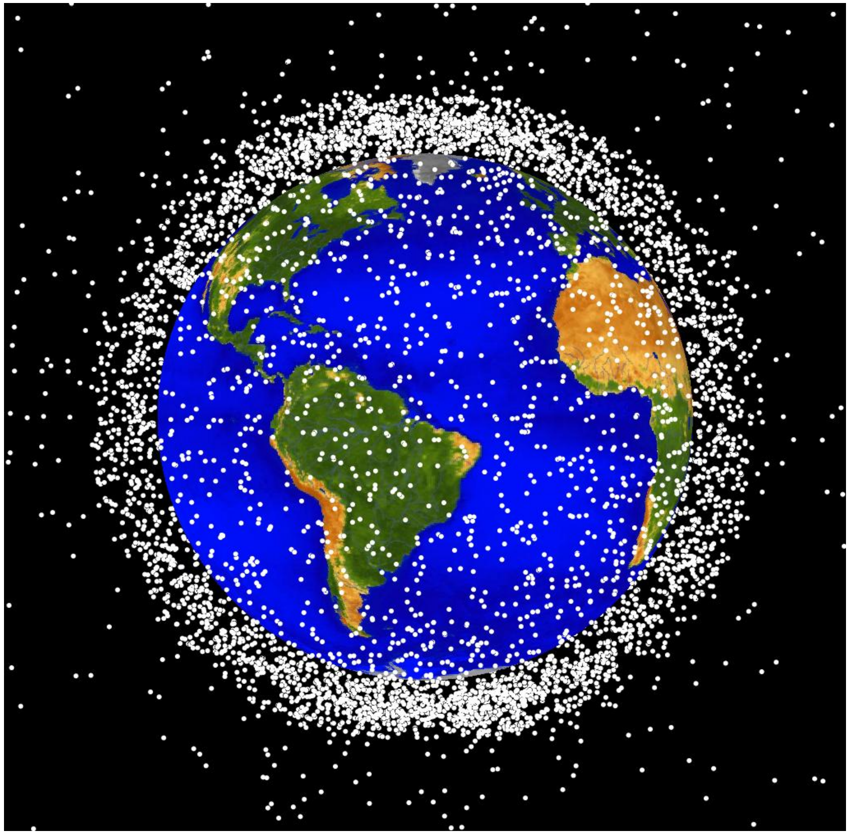
1990

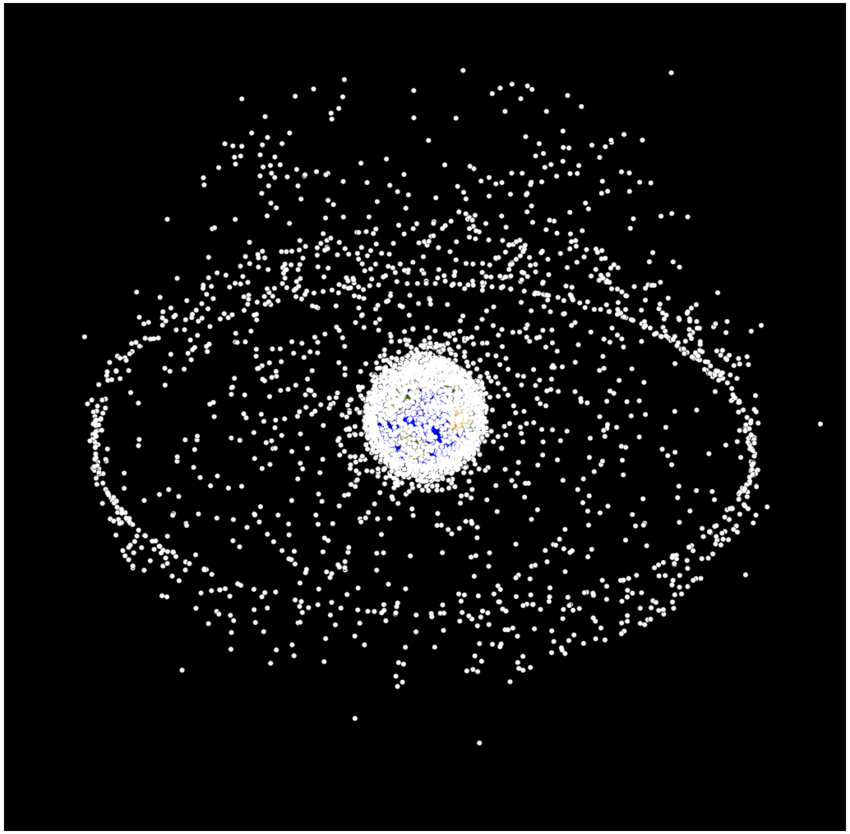




Cataloged objects >10 cm diameter

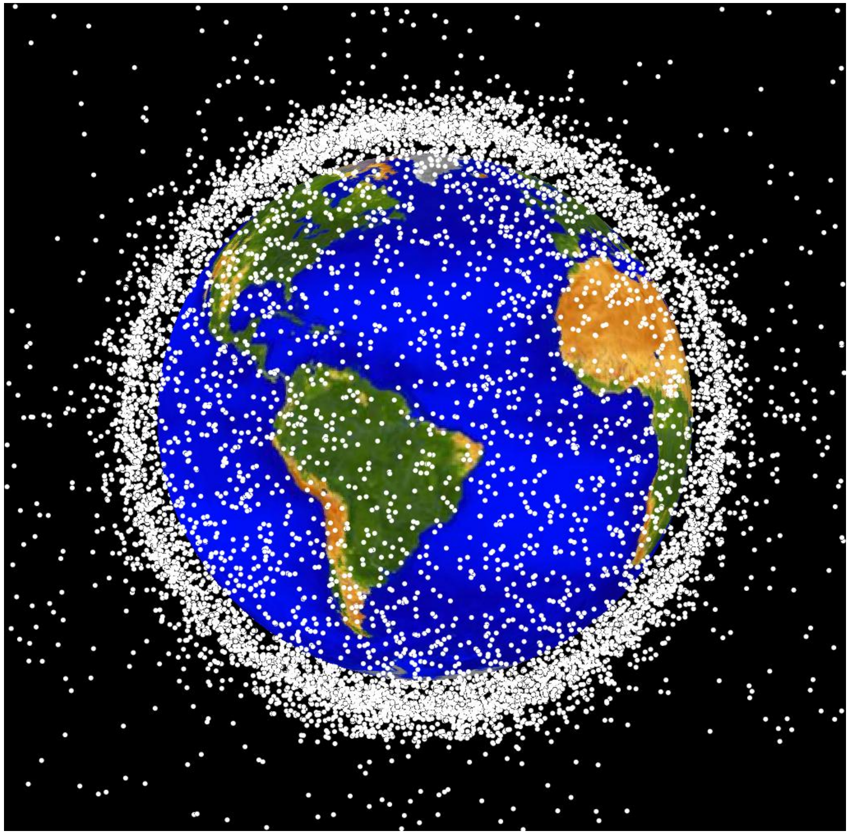
2000

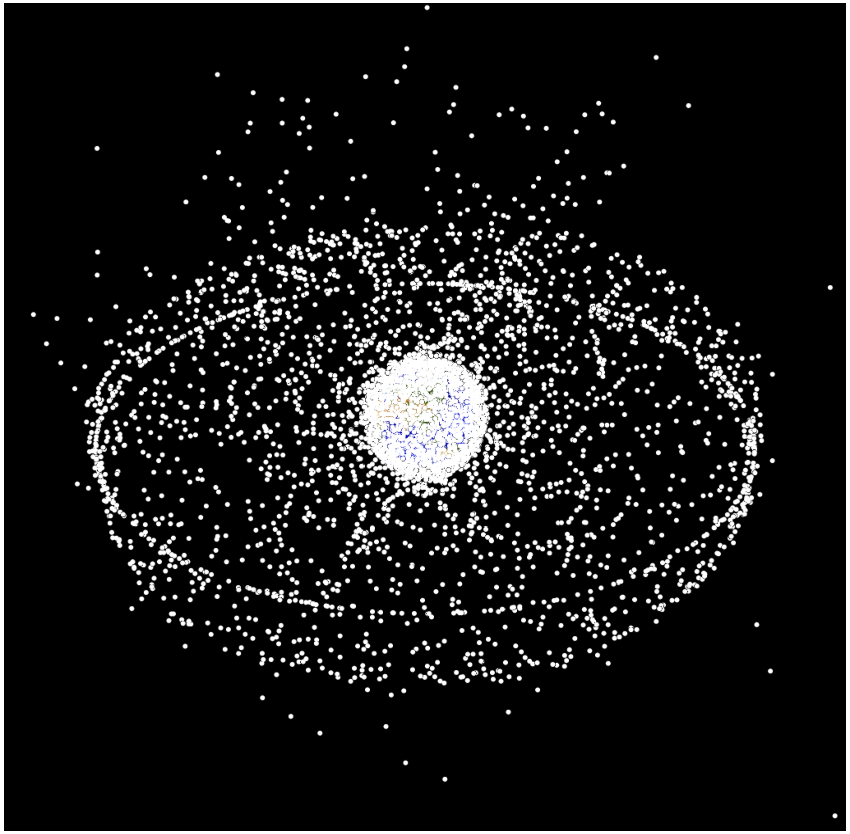




Cataloged objects >10 cm diameter

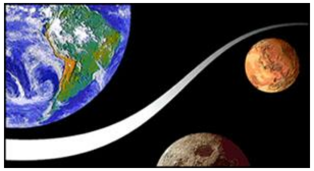
August 2009





Cataloged objects >10 cm diameter

MMOD Environment Models (cont.)

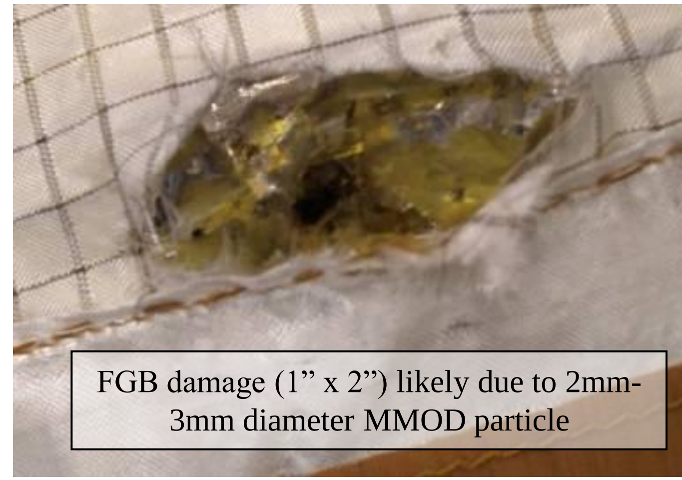


- Orbital Debris is the predominate threat in low Earth orbit
  - For ISS, debris represents approximately 2/3^{rds} of the MMOD risk
  - For missions to the Moon, L1, or elsewhere, OD risk will need to be assessed for time period spacecraft resides in LEO
- Meteoroid model (MEM) provided by MSFC
  - http://www.nasa.gov/offices/meo/home/index.html
  - Meteoroid environment (MEM): 11-72 km/s
    - Average 22-23 km/s
  - MM environment model is subject to change (new release of MEM is pending)
- Meteoroid risk is influenced by Earth focusing (gravitational) factor and Earth shadowing while in Earth orbit
  - Meteoroid risk far from Earth is typically somewhat less compared to meteoroid risk in Earth orbit (for Earth-Moon space)

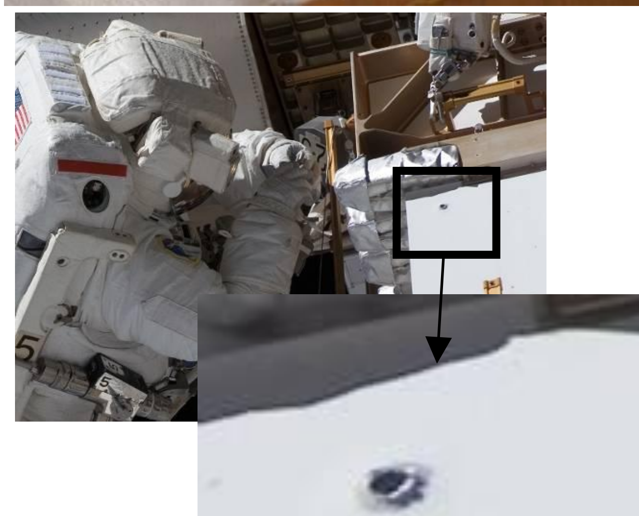
MMOD Damage to spacecraft

- Several ISS and Shuttle MMOD damages appear to have been caused by >1mm diameter MMOD particles
  - FGB compressor damage due to 2mm-3mm diameter particle
  - P6 radiator damage due to 3mm-5mm particle
  - SM solar array damage due to >2mm particle
  - STS-118 radiator damage due to high density 1mm particle

- Good agreement between actual damage to predictions for ISS Pressurized Logistics Module and Shuttle (damage identified after return to ground)



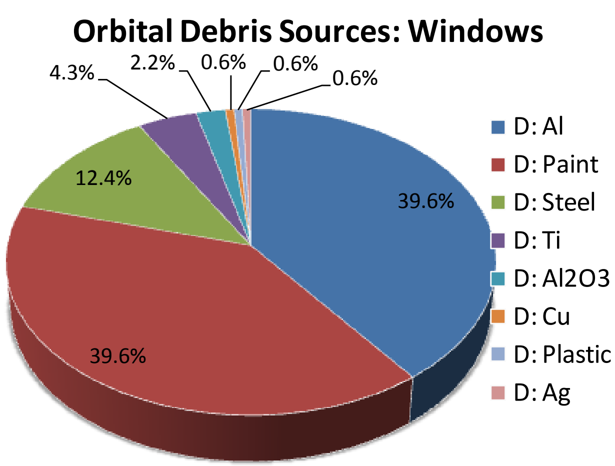
FGB damage (1" x 2") likely due to 2mm-3mm diameter MMOD particle

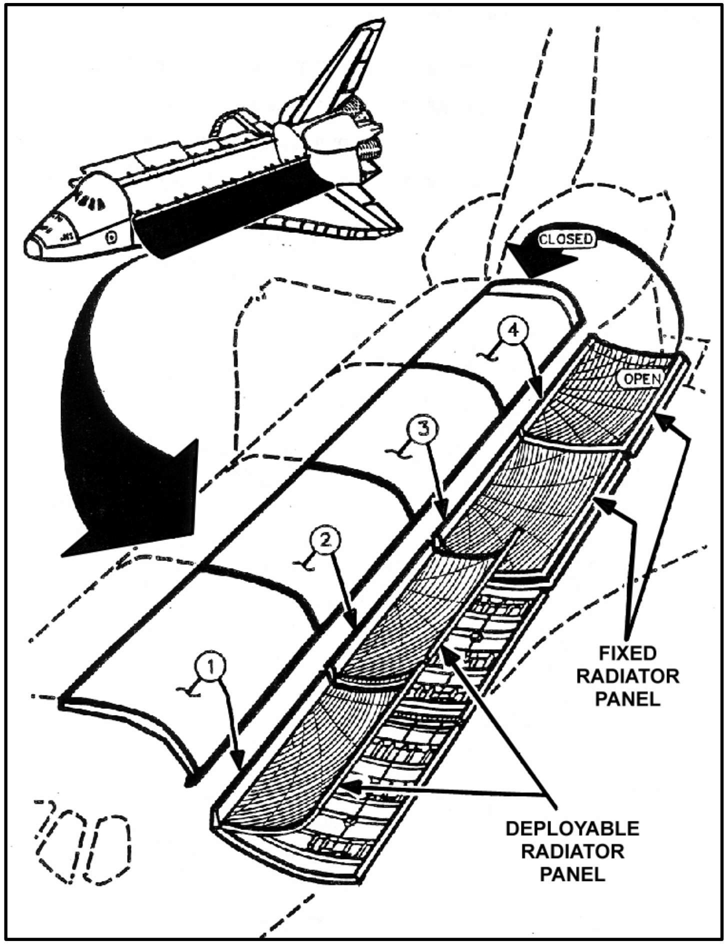


P6 radiator damage noted during STS-118 (0.75" diameter) likely due to 3-5mm diameter x 1mm thick MMOD particle

Shuttle MMOD Impacts

- Over 2800 MMOD impacts have been recorded to Shuttle radiators, windows, nose cap and wing leading edge (about 10% of vehicle)
- From STS-114 (July 2005) through STS-133 (Feb. 2011):
  - 273 window impacts
  - 303 radiator impacts
  - 254 NC/WLE impacts
  - Average 41 MMOD impacts per mission

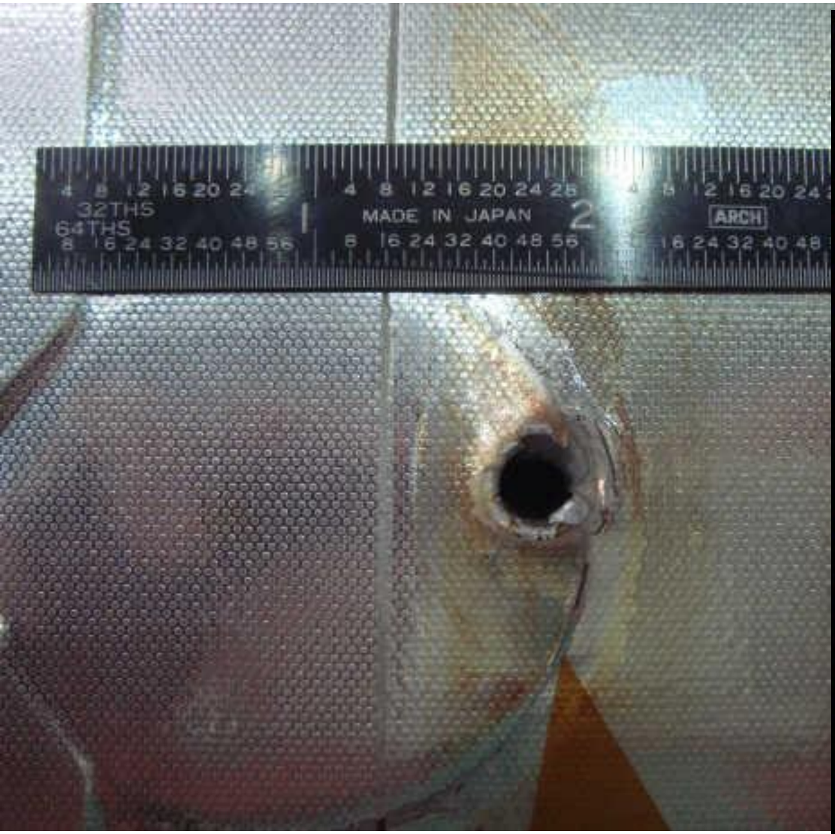




STS-118 LH4 Radiator Damage

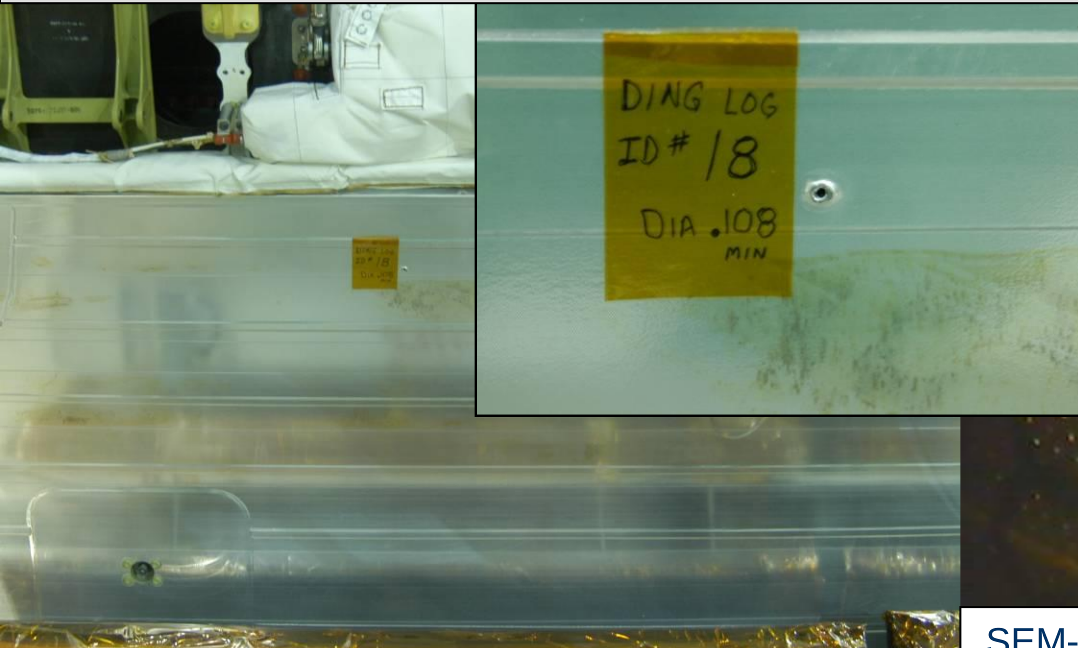
- Hole (0.216 inches diameter) through front facesheet (and doubler), and 0.5in to 0.75in diameter in back facesheet. Also went through thermal blanket behind radiator (two places) and left deposits on payload bay door.

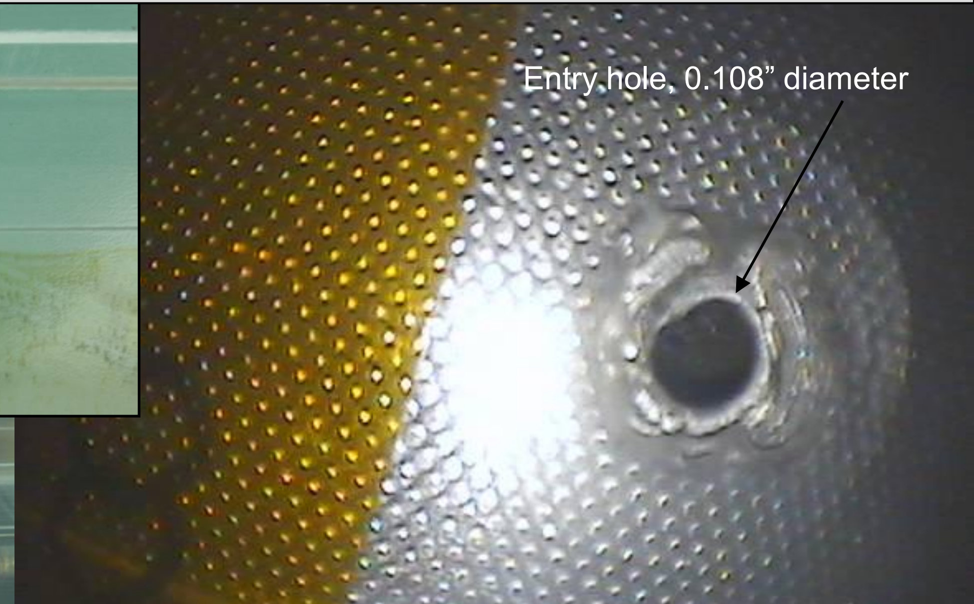
Front Facesheet Damage



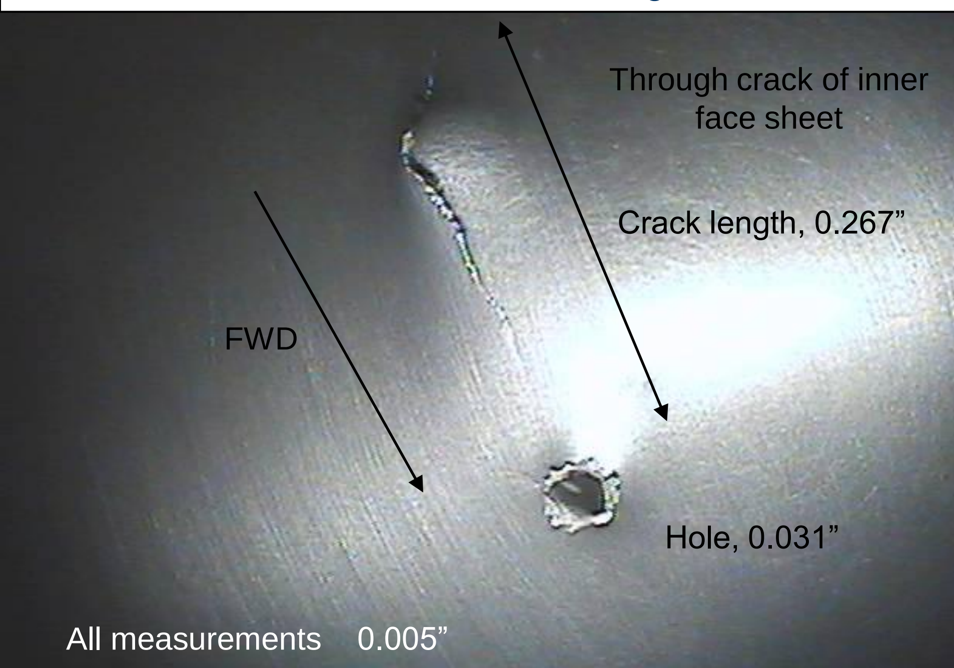
Back Facesheet Damage

MMOD Impact on STS-115 (OV-104) RH4 Radiator Panel

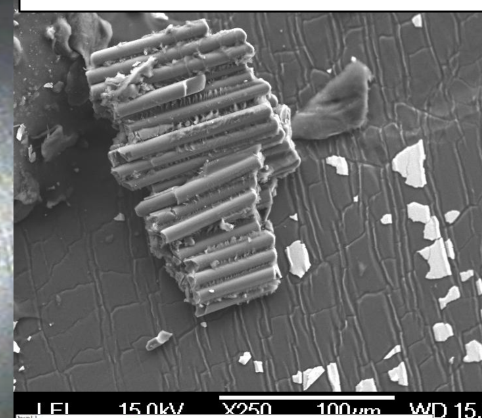


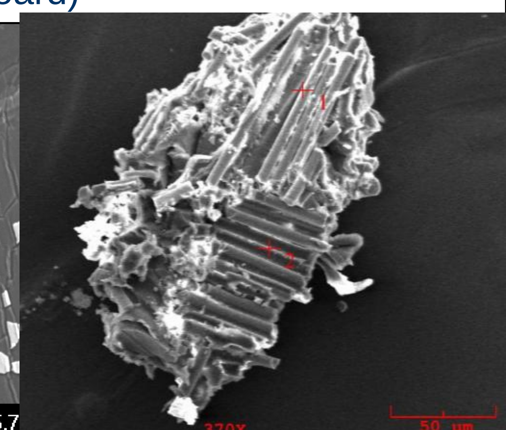


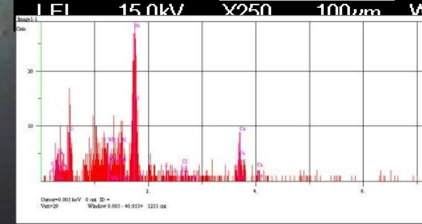
Inner face sheet damage



SEM-EDX analysis indicates damage caused by orbital debris: ceramic fiber-organic matrix composite (circuit board)

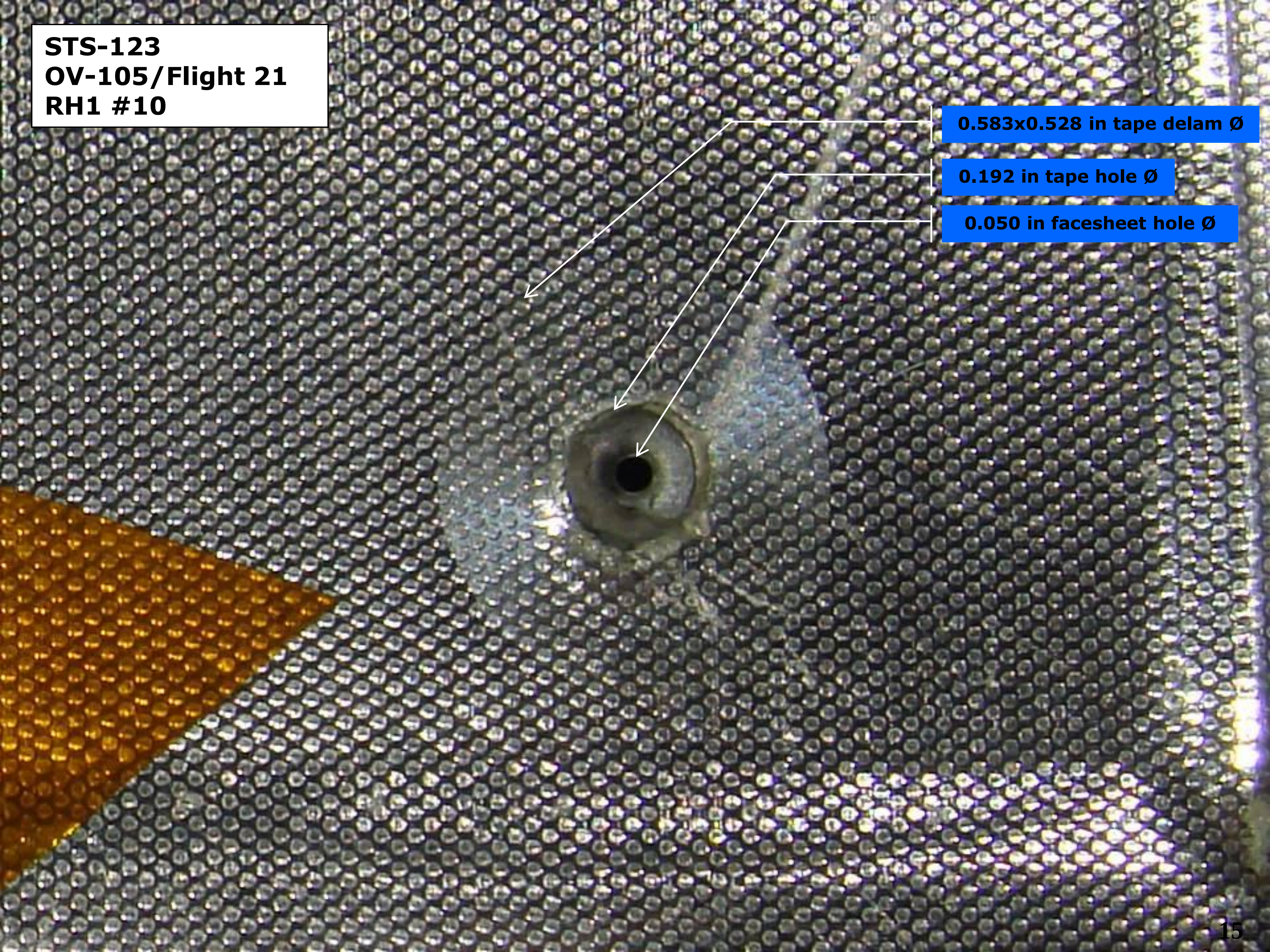






ls Research and Exploration Science

Fibers contain Si, Al, Ca, Mg, O


STS-123
OV-105/Flight 21
RH1 #10
0.583x0.528 in tape delam Ø
0.192 in tape hole Ø
0.050 in facesheet hole Ø

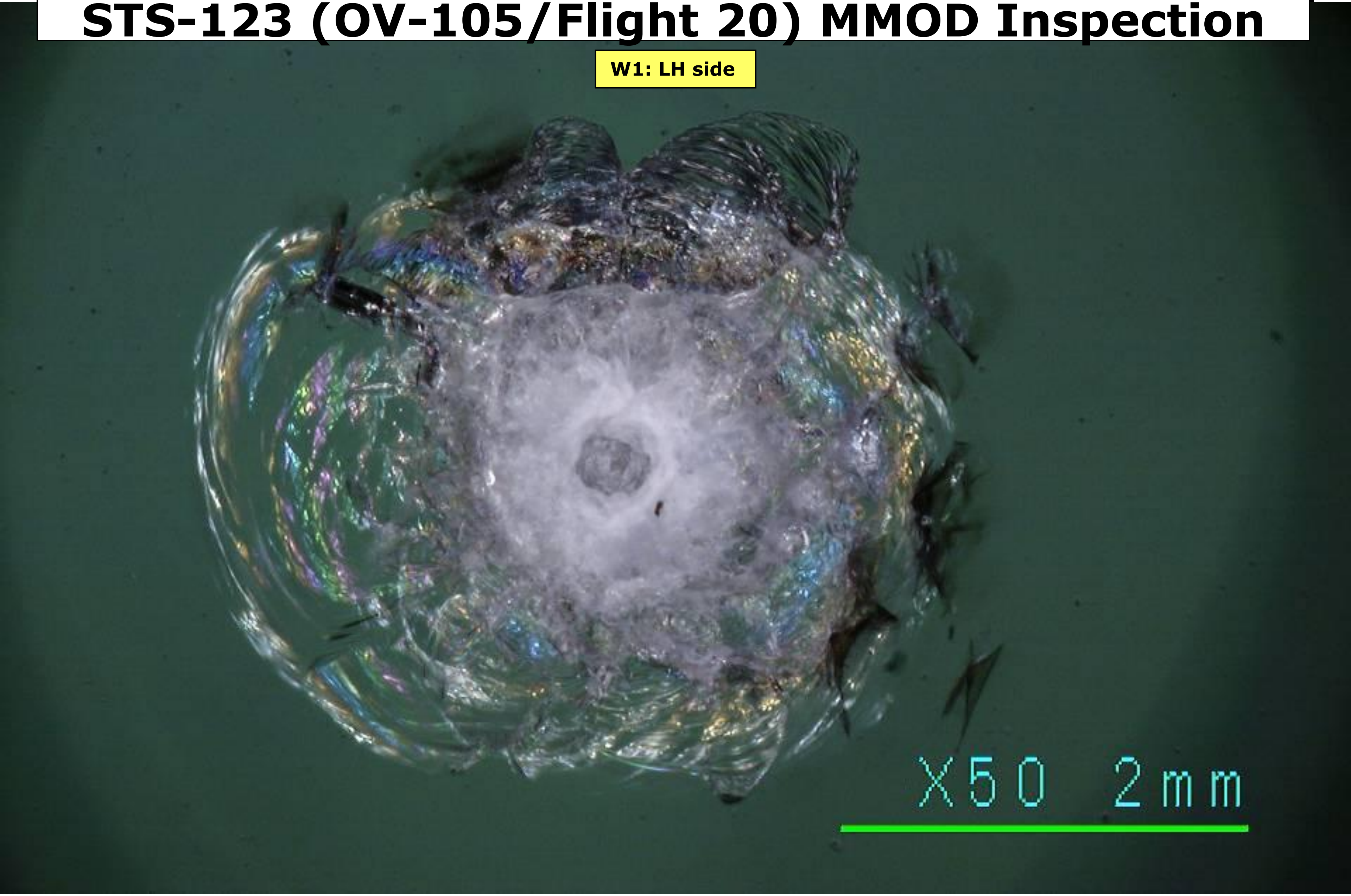
STS-123 (OV-105/Flight 21) MMOD Inspection

W1: LH side

Depth=0.389 mm (0.0153 in)
Extent=3.66x3.25 mm (0.14 x 0.13 in)

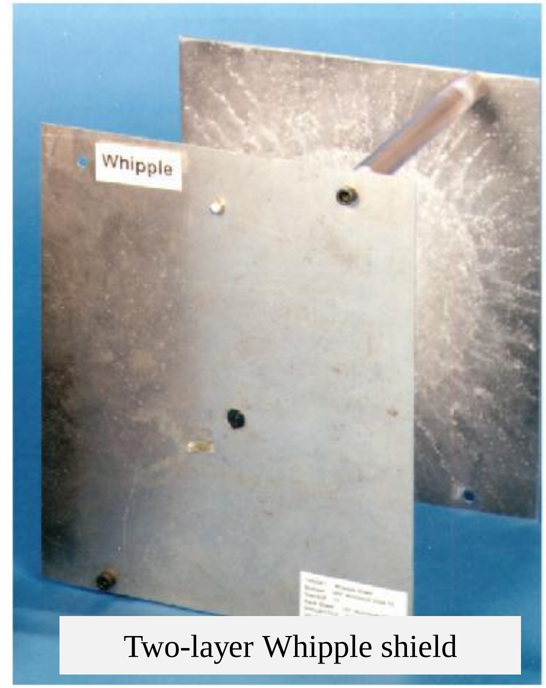
STS-123 (OV-105/Flight 20) MMOD Inspection

W1: LH side



Hypervelocity impact effects

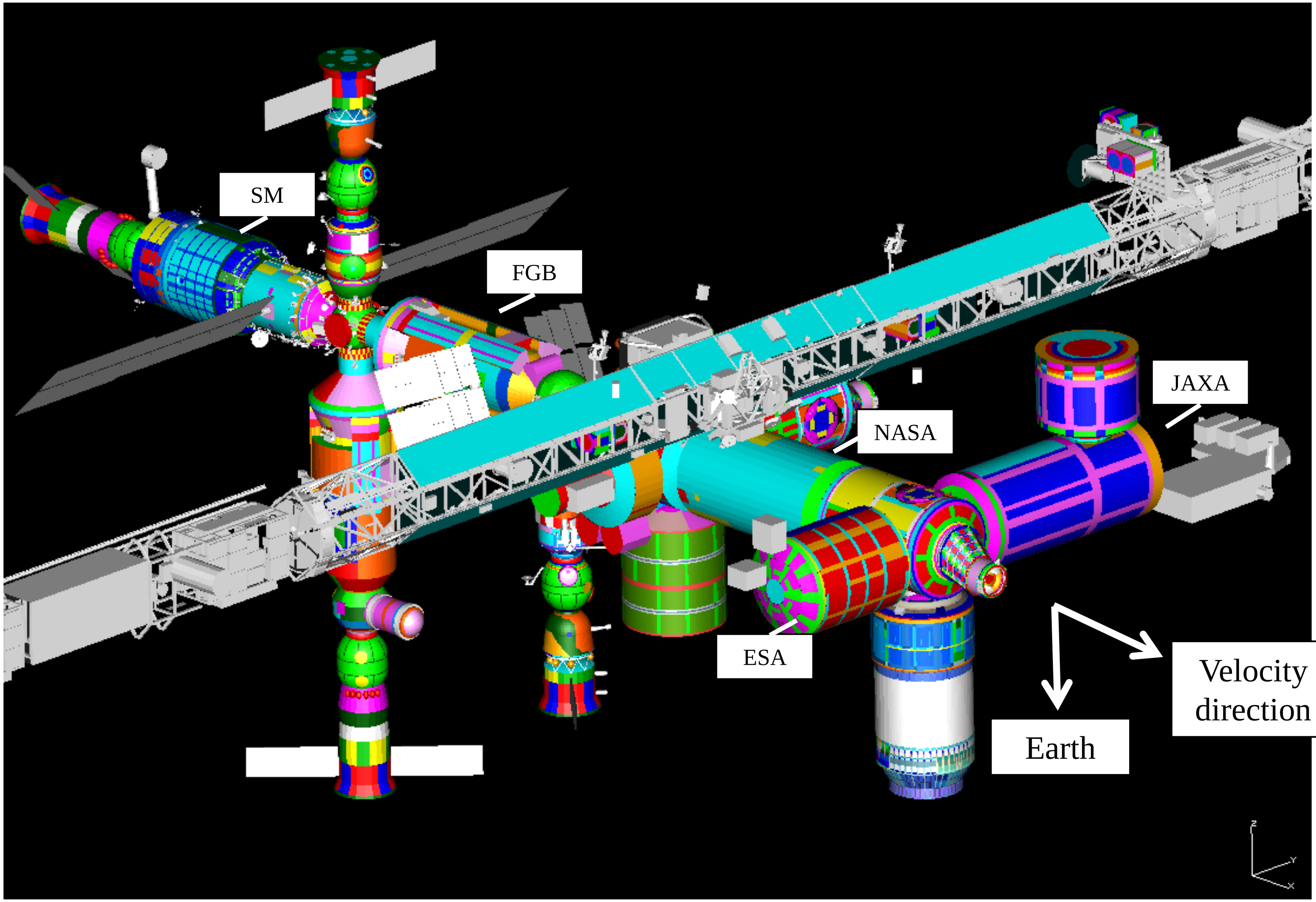
Monolithic target



Two-layer Whipple shield

- At hypervelocity, small particles can cause a lot of damage
  - High velocity MMOD particles represent a substantial threat to spacecraft which typically are constructed with light-weight materials to save mass
  - Rule of thumb: at 7km/s, aluminum sphere can penetrate completely through an aluminum plate with thickness 4 times the sphere's diameter
  - A multi-layer spaced shield provides more effective protection from hypervelocity impact than single layer (total shield thickness < projectile diameter)

ISS MMOD shielding
finite element model for Bumper code MMOD risk assessments

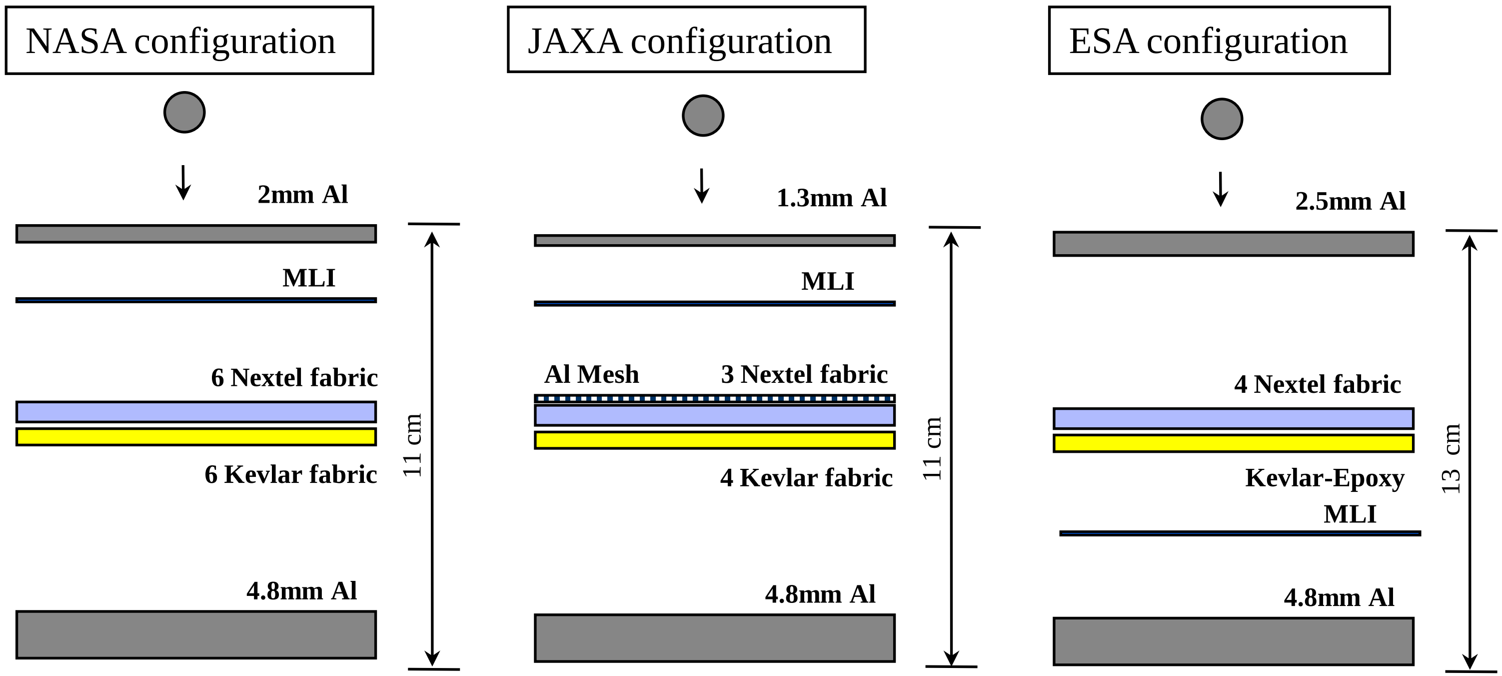


Each color represents a different MMOD shield configuration

ISS "Stuffed Whipple" Shielding

(Typical Configurations Illustrated)

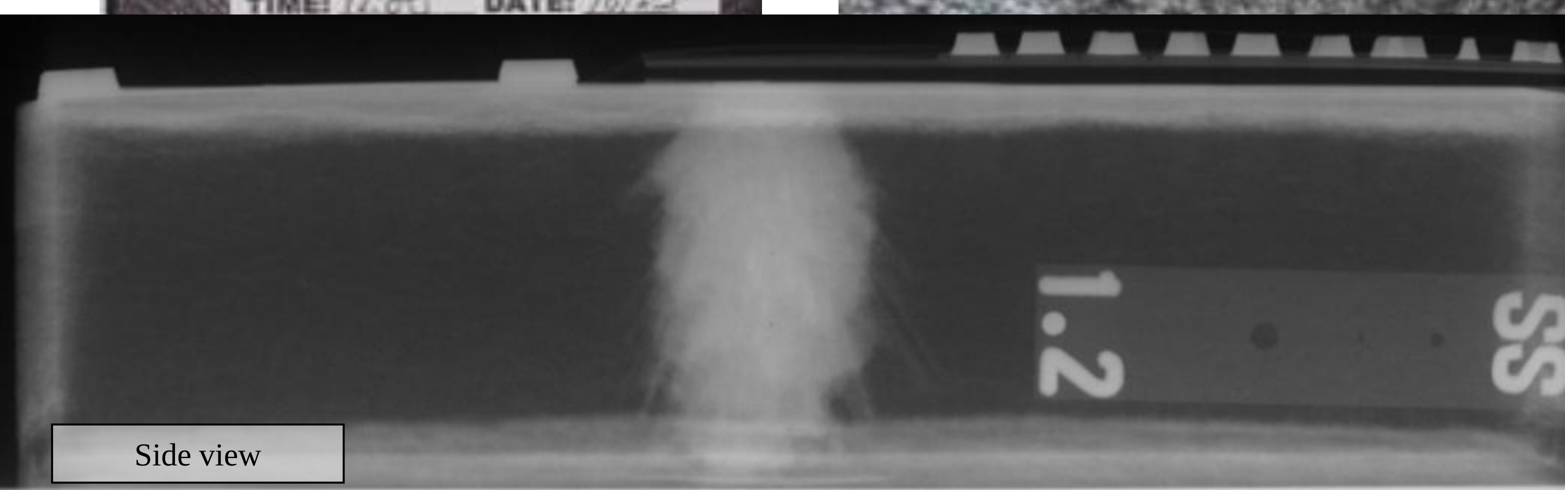
- US, JAXA and ESA employ "Stuffed Whipple" shielding on the areas of their modules exposed to greatest amount of orbital debris & meteoroids impacts
  - Nextel and Kevlar materials used in the intermediate bumper
  - shielding capable of defeating 1.3cm diameter aluminum sphere at 7 km/s, normal impact



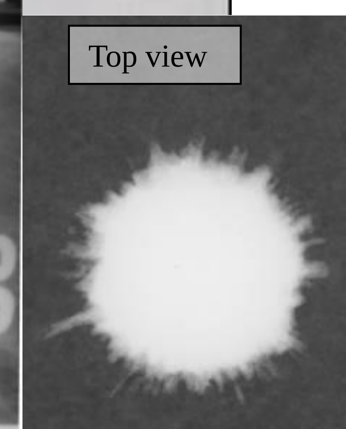
Typical Thermal Protection System (TPS) Tile Impact Damage

AETB-8 Test #2 HITF-7469

projectile: 2.4mm (3/32”) diameter Al 2017T4, 7.00 km/s, 0^{o} impact angle



Side view



Top view

MMOD Risk Summary

- MMOD Risk estimates:
  - Shuttle mission thermal protection system (TPS) damage leading to loss-of-vehicle: 1 in 250 without TPS inspection,1 in 400 with late inspection per flight
  - Orion TPS damage leading to loss-of-vehicle & crew during 210day ISS mission: 1 in 400 without inspection, 1 in 1800 with TPS inspection
  - ISS MMOD risk for penetration of pressure shell of crew modules over next 15 years (i.e., causing air leak): 1 in 3

- More information available:
  - JSC Hypervelocity Impact Technology (HVIT) website: http://ares.jsc.nasa.gov/ares/hvit/index.cfm
  - NASA TP-2003-210788, Meteoroid/Debris Shielding
  - NASA TM-2009-214785, Handbook for Designing MMOD Protection
  - NASA TM-2003-212065, Integration of MMOD Impact Protection Strategies into Conceptual Spacecraft Design
  - NASA TM-2009-214789, MMOD Shield Ballistic Limit Analysis Program

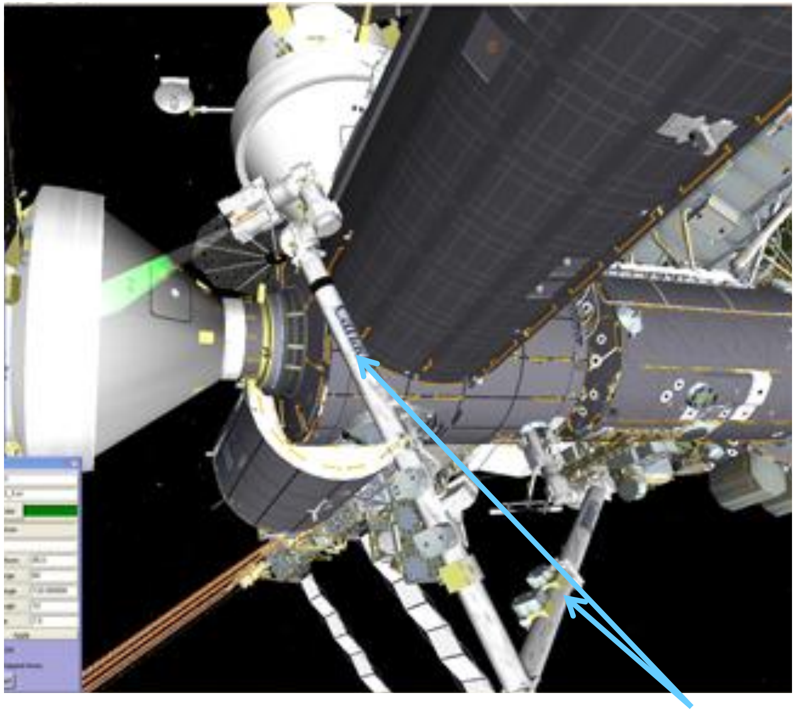
MMOD Inspection Sensor Capability Development

- Determine risk
- Determine inspection criteria
- Define needed sensor capability
- Select or build sensor packages and include illuminator as needed
- Perform Validation, Verification, and Certification Testing
  - Use blind/subjective testing where possible
- Build generic and mission-specific procedures
  - Robotic scan trajectories (e.g. field-of-view and exposure-time dependent)
  - Crew robotic, sensor op, and inspection procedures
    - Autonomous to crew
    - Interactive with Ground Support
    - If no illuminator, include ambient illumination planning
- Create document tailoring sensors and combinations of sensors to specific inspection needs (e.g. Space Shuttle focused-inspection “Rosetta Stone”) to facilitate quick in-flight procedure building
- Assemble Damage Assessment Team (DAT) and train them on sensor output data
- Conduct inspection-related simulations and include DAT participation.

General Concept for External Inspection

- Perform a full-surface survey
  - Use spacecraft-to-spacecraft photography, robotics, a free-flyer, or surface crawler to systematically image the entire external surface of the reentry spacecraft
    - For high probability of detection (PoD), image the surface such that at least 4 resolution elements (resels) bridge the critical dimension of the smallest critical-sized damage.
    - Perform a coverage analysis to ensure the entire surface was observed
  - Screen the survey imagery
    - Use redundant, independent teams to compare inspection imagery with baseline images of the same surface
    - Enhance process with automatic feature detection as available
    - Post all anomalous features or “Regions of Interest” (ROIs) to a web-based log for disposition by a Damage Assessment Team (DAT)
  - Disposition Regions of Interest and determine need for Focused Inspection
    - If no Focused Inspection needed, declare the spacecraft safe to re-enter
- If needed
  - Perform close-range, high-resolution Focused Inspection of candidate ROIs.
  - Plan repair or safe haven or declare the spacecraft safe to reenter.
  - Repair, if needed, and perform post-repair inspection to examine success of repair.
- Perform post-flight inspection and evaluate on-orbit inspection performance

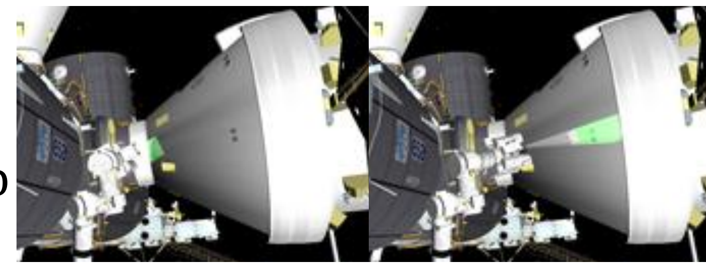
Survey Inspection of Visiting Vehicle at Node 2 Forward



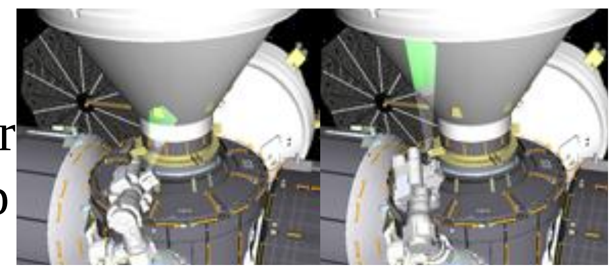
Space Station Remote Manipulator System (SSRMS) arm, based at the Node 2 Power/Data Grapple Fixture (PDGF) with Latching End Effector (LEE)-based MSS Camera inspecting a Visiting Vehicle (VV)

VV-Zenith sweep

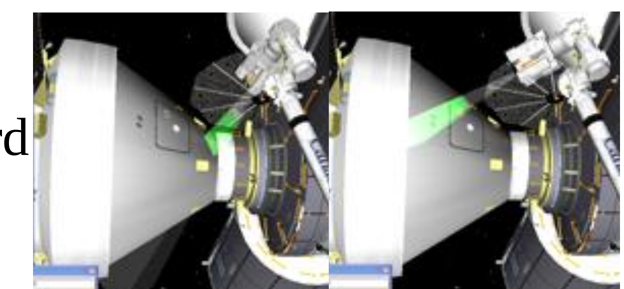
-Port sweep



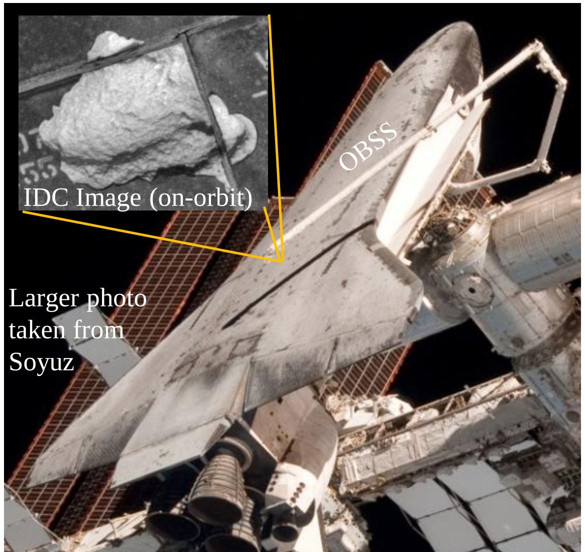
-Nadir sweep



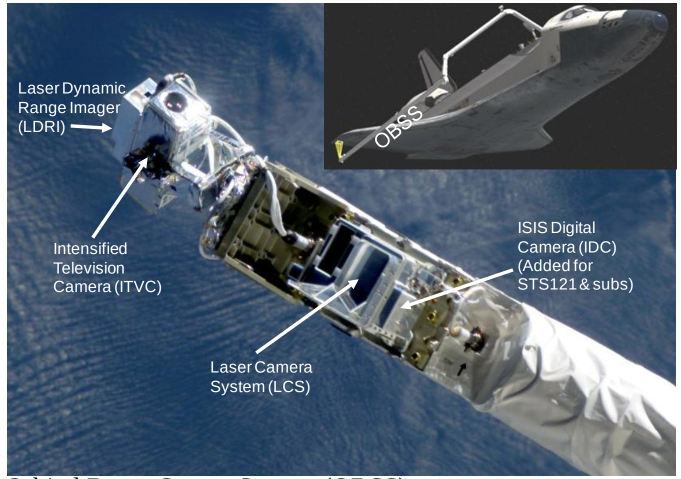
-Starboard sweep



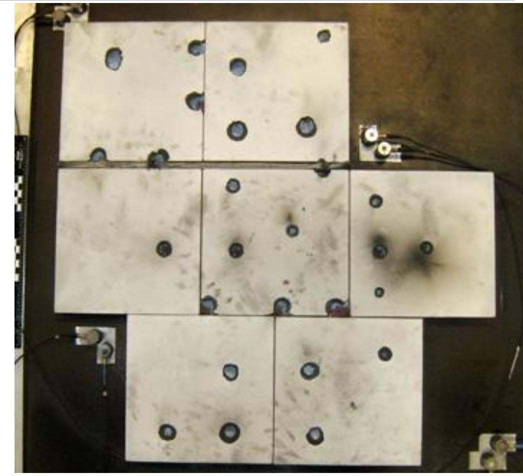
Example Damage and Sensing



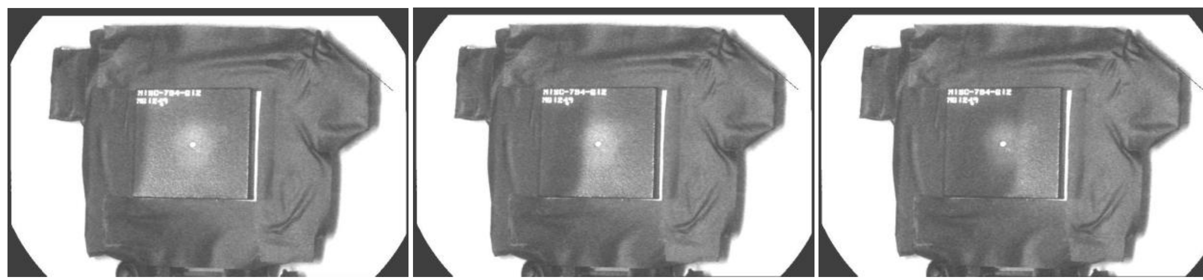
STS-134: OBSS Positioned for focused Inspection of Tile Gouge (Ascent Related Damage).



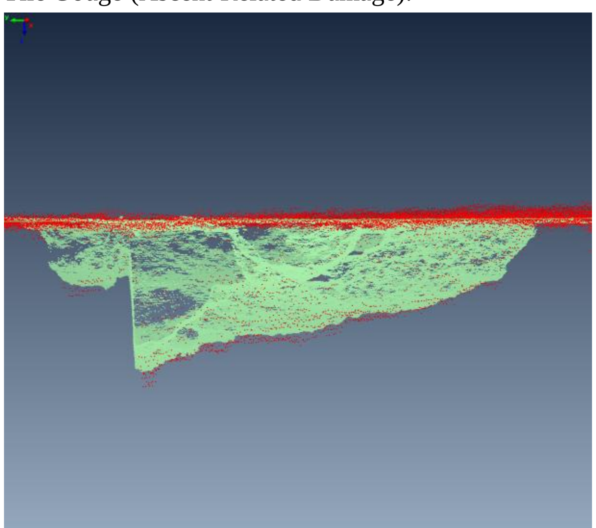
Orbital Boom Sensor System (OBSS)



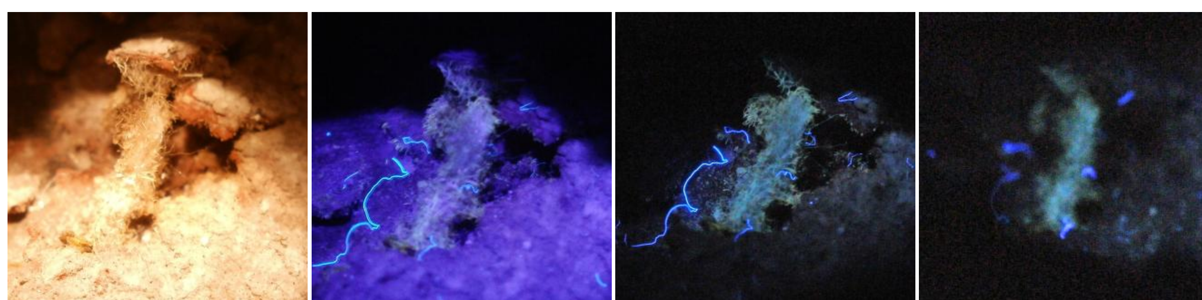
TPS Tile Array for Hypervelocity Impact Testing



LDRI images of hypervelocity impact damage at tile center. Note strong return from impact cavity due to line-of-sight illumination. Also note that shadow w.r.t simulated sun has little effect on ability to inspect the surface.

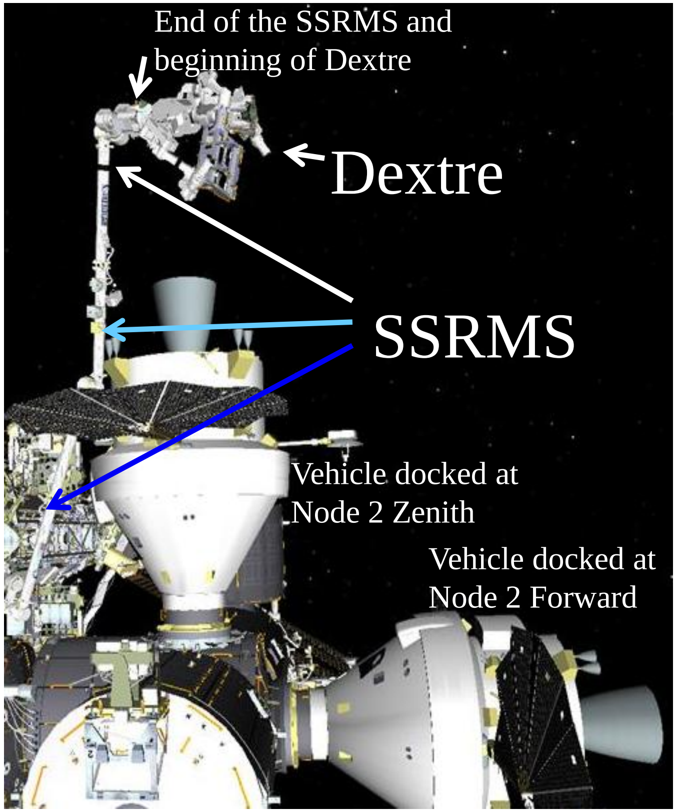


STS-134 tile gouge 3D point clouds: LCS (on-orbit) red, Mold Impression Laser Tool (MILT, post-flight) green

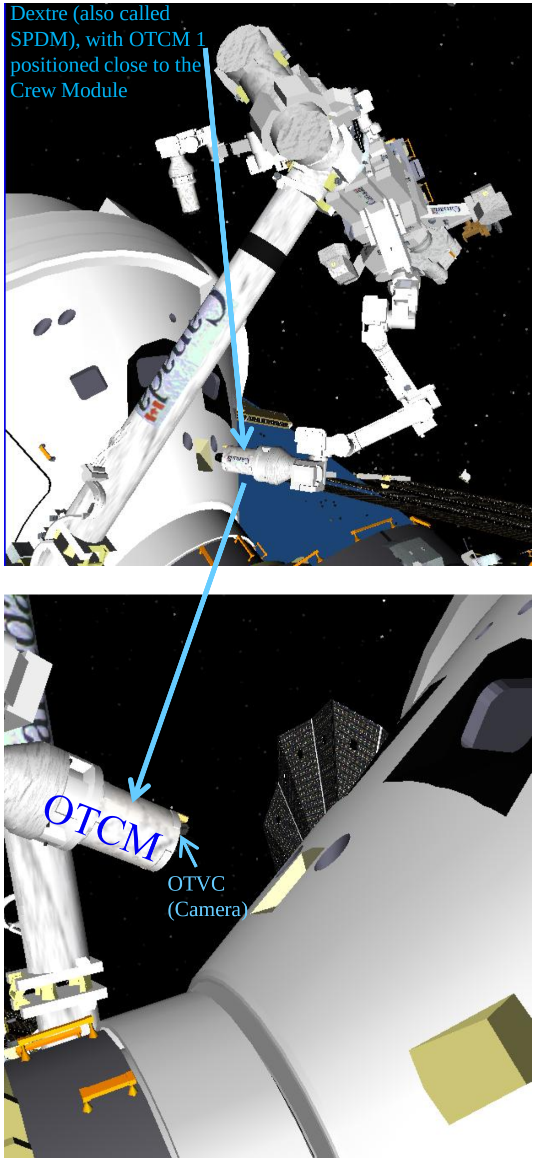


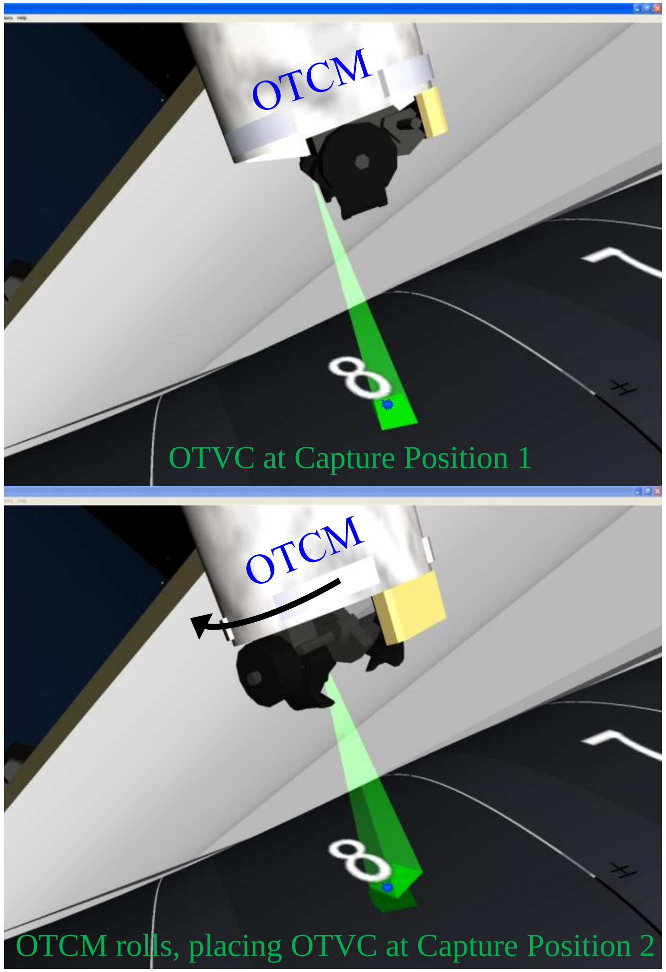
TPS material; Left: visible-band illumination Remainder: Fluorescence from different UV wavelengths

Focused Inspection of a Visiting Vehicle with Using Dextre



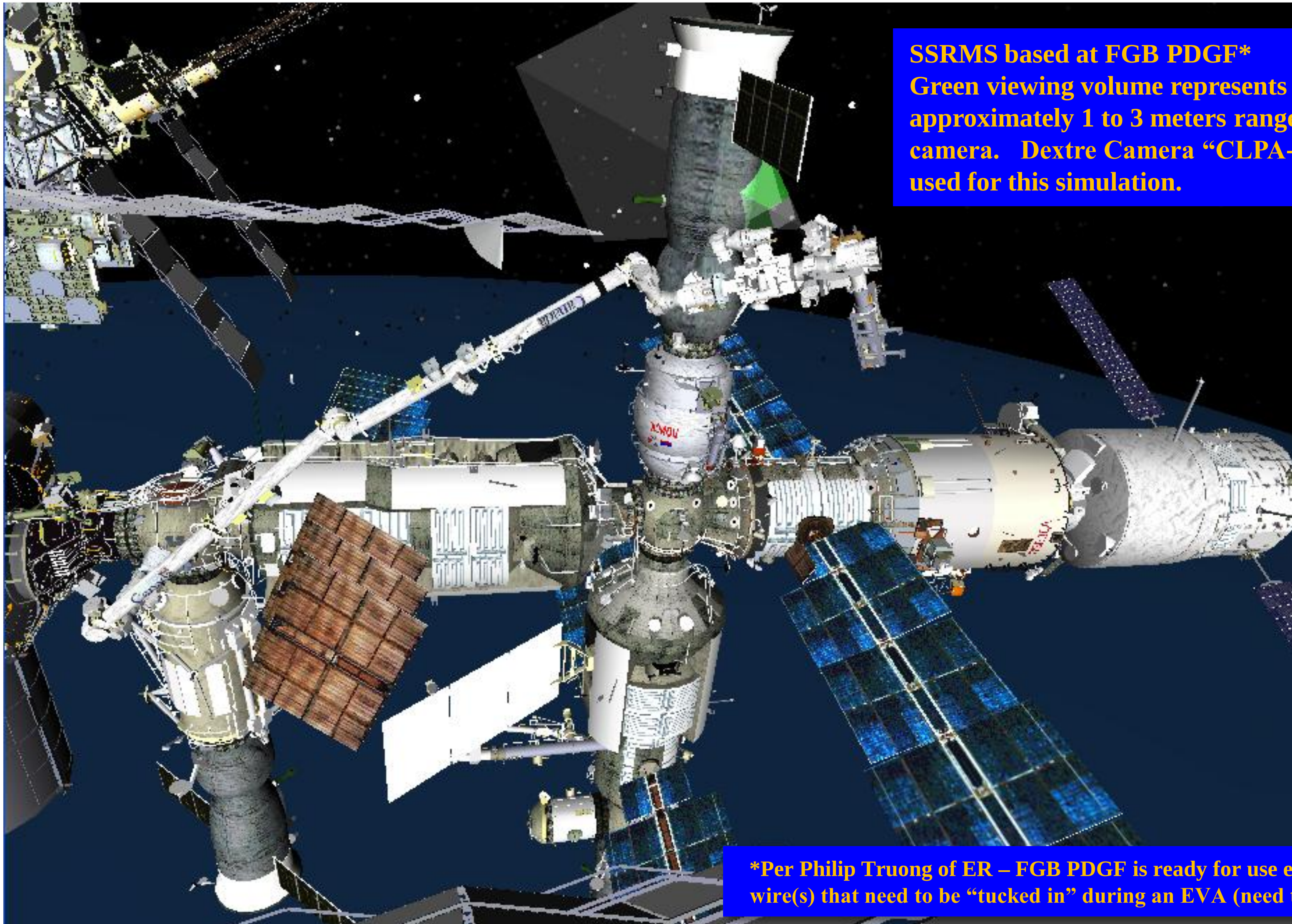
Visiting vehicles docked at ISS, with Dextre mounted on the SSRMS preparing for an engine bell inspection. Note ample reach for a vehicle the approximate size of the Orion MPCV.



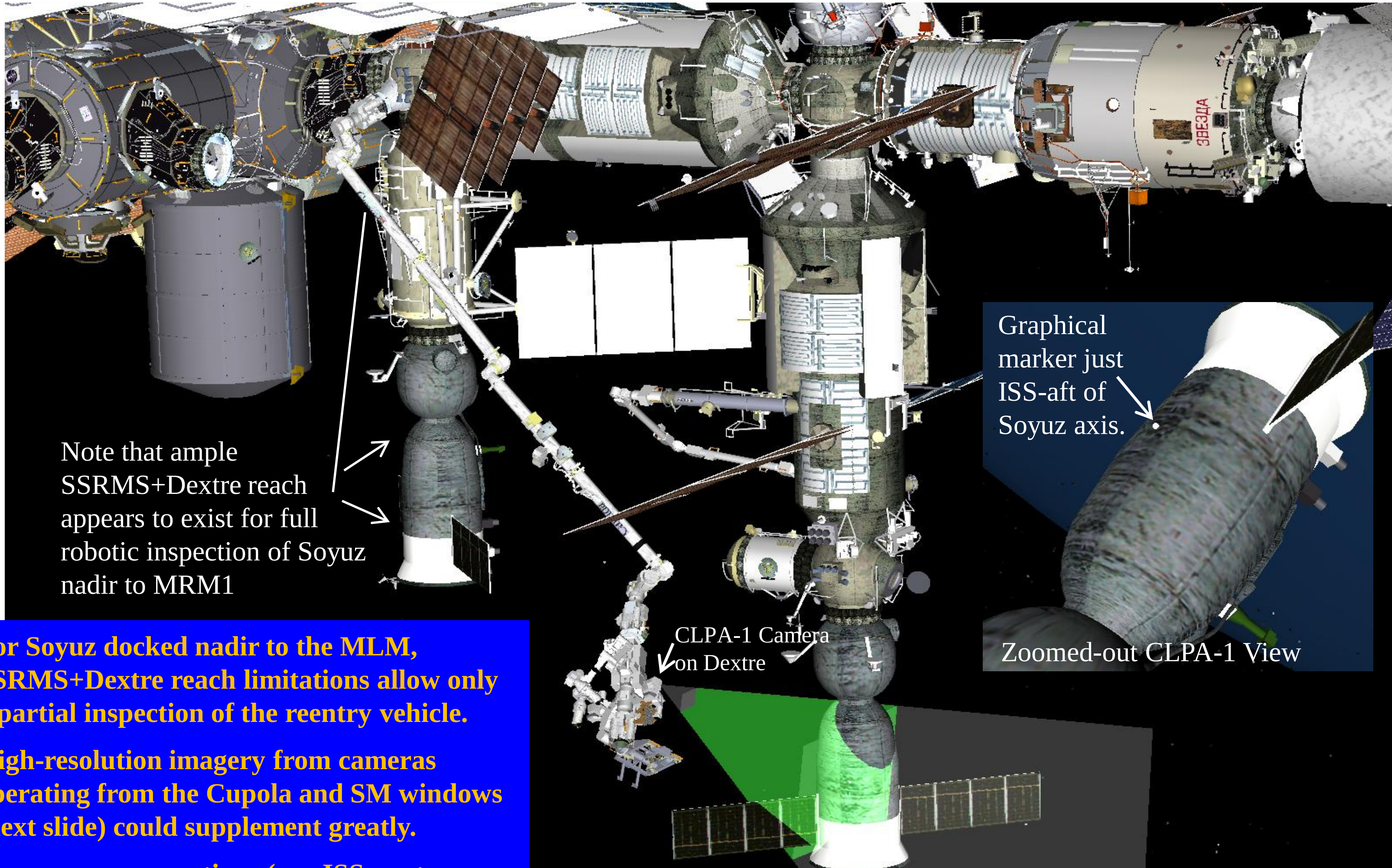


OTCM Roll for Stereo - Allows close-range OTVC (camera) to capture a medium-high-resolution “stereo pair” for 3D measurements

No Reach Issues Predicted for Soyuz at MRM2 (SM Zenith)

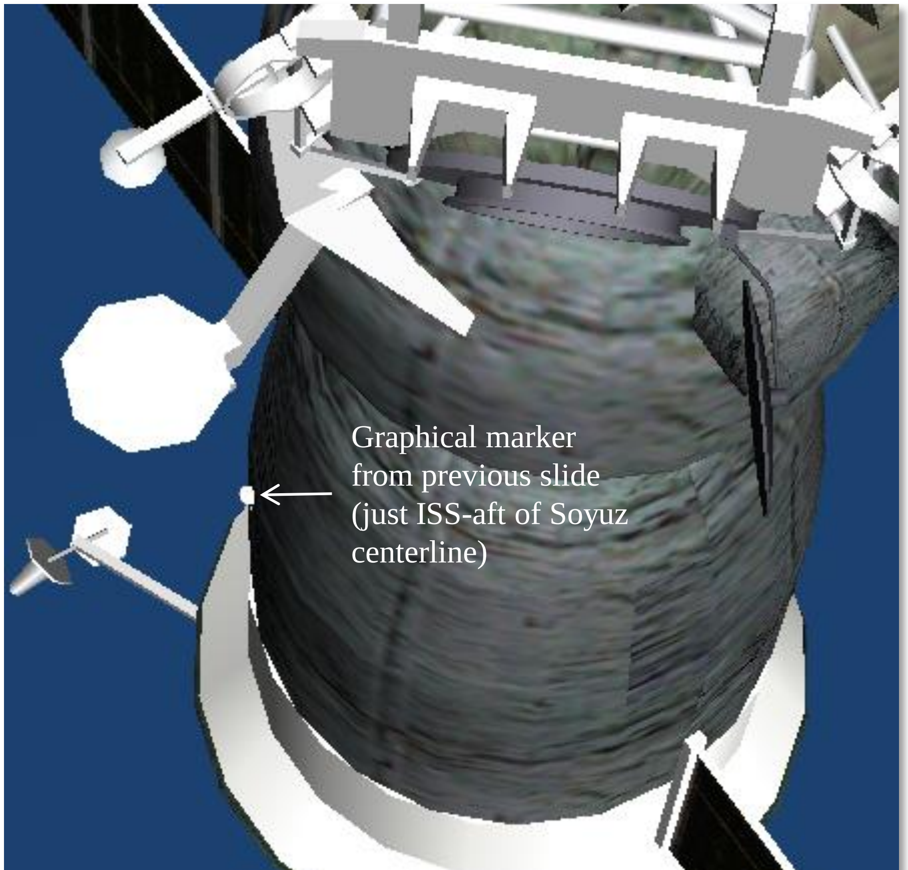


Reach Is Predicted to Be Issue for Aft Side of Soyuz at MLM (Nadir)

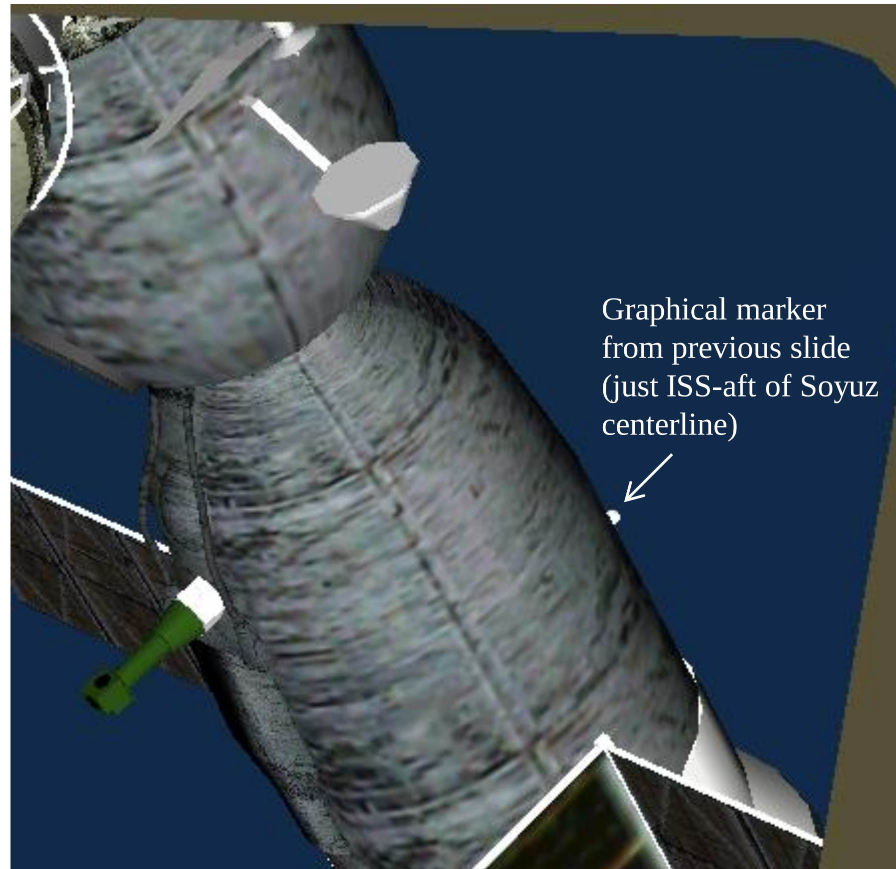


- **For Soyuz docked nadir to the MLM, SSRMS+Dextre reach limitations allow only a partial inspection of the reentry vehicle.**
- **High-resolution imagery from cameras operating from the Cupola and SM windows (next slide) could supplement greatly.**
- **However, some portions (e.g. ISS-port surface of Soyuz) may not be imaged to adequate resolution while the spacecraft is docked at this location (TBD).**

Aft Side of Soyuz at MLM Nadir From SM and Cupola Windows



Simulated still image of ISS-aft Soyuz surface from SM window.



Simulated still image of ISS-fwd Soyuz surface Cupola window.

Imager Based Damage Detection and Measurement Capability

- ISS Robotic Based Imagers – TPS Damage Detection (0.25” MPCV* TPS-type entry hole detection)
  - >99% Probability of Detection (black or white tiles), assuming up to 3 redundant/independent screening teams.
  - Robotic trajectories not defined, so no timeline for above PoD for full-surface inspection
- ISS Robotic Based Imagers - Measurement:
  - Transverse measurement accuracy (w.r.t. line of sight): ~0.07”
  - Thermal Protection System (TPS) Tile cavity ***depth*** measurement accuracy: ~0.2” (Desired ~0.04” or 1 mm). Sensitive to entry hole width and ability to illuminate internal cavity.
- ISS Visiting Vehicles – Fly Around Imagery, 600’ Range (example)
  - Transverse measurement accuracy (D3X, 105 mm lens) ~0.6”
    - Corresponding damage detection resolution ~2.25”
- exo-LEO Reentry Vehicle TPS Inspection Capability
  - **TBD**

*MPCV spacecraft not currently baselined for ISS missions (strategic backup only)

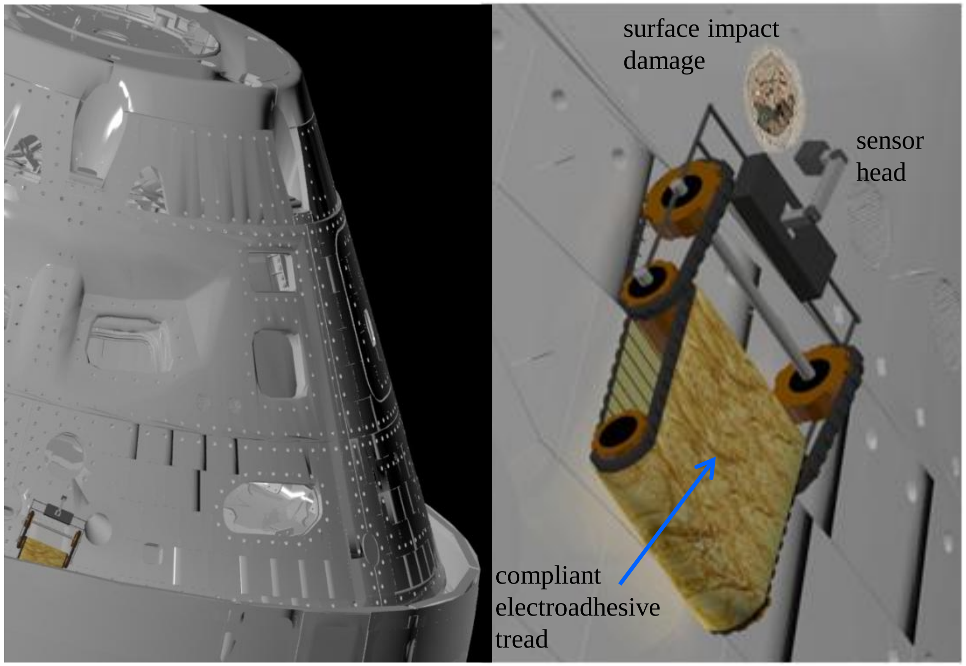
exo-LEO Inspection Concepts

Enabling Technologies for articulating and mobile robots are being monitored by NASA personnel such as George Studor and the Image Science and Analysis Group

- Articulated Robotics
  - Tendril (Flexible Borescope): http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1639170&userType=inst
- Free-flyers (Feature high-resolution imagers and near line-of-sight illumination)
  - AERCam (tested on-orbit as Sprint and further developed in the laboratory)
    - http://aercam.jsc.nasa.gov/aercam.pdf
  - PicoSat (currently operation on-orbit since STS-135)
    - http://en.wikipedia.org/wiki/PSSC-2
    - http://www.aero.org/publications/crosslink/summer2009/06.html
- Surface Crawler Inspection Robots
  - Electro-adhesion technology in advanced state of development by SRILinks: →
    - http://www.sri.com/rd/electroadhesion.html
    - http://www.sri.com/rd/WallClimbtoWindow.mov
  - Gecko-inspired Synthetic Adhesive (GSA) technology
    - http://www.youtube.com/watch?v=odAifbpDbhs

Surface-crawler Inspection Robot

- For detection and measurement of damage, especially from MMOD strikes
  - Stereo Imager
  - Penetrating Sensor
- Telerobotic or autonomous control
- Targets LEO **and exo-LEO** missions
- Leverages recent advances in electric-field-based adhesion technology
  - Robot can roll along surface without detaching
  - Very low power requirements

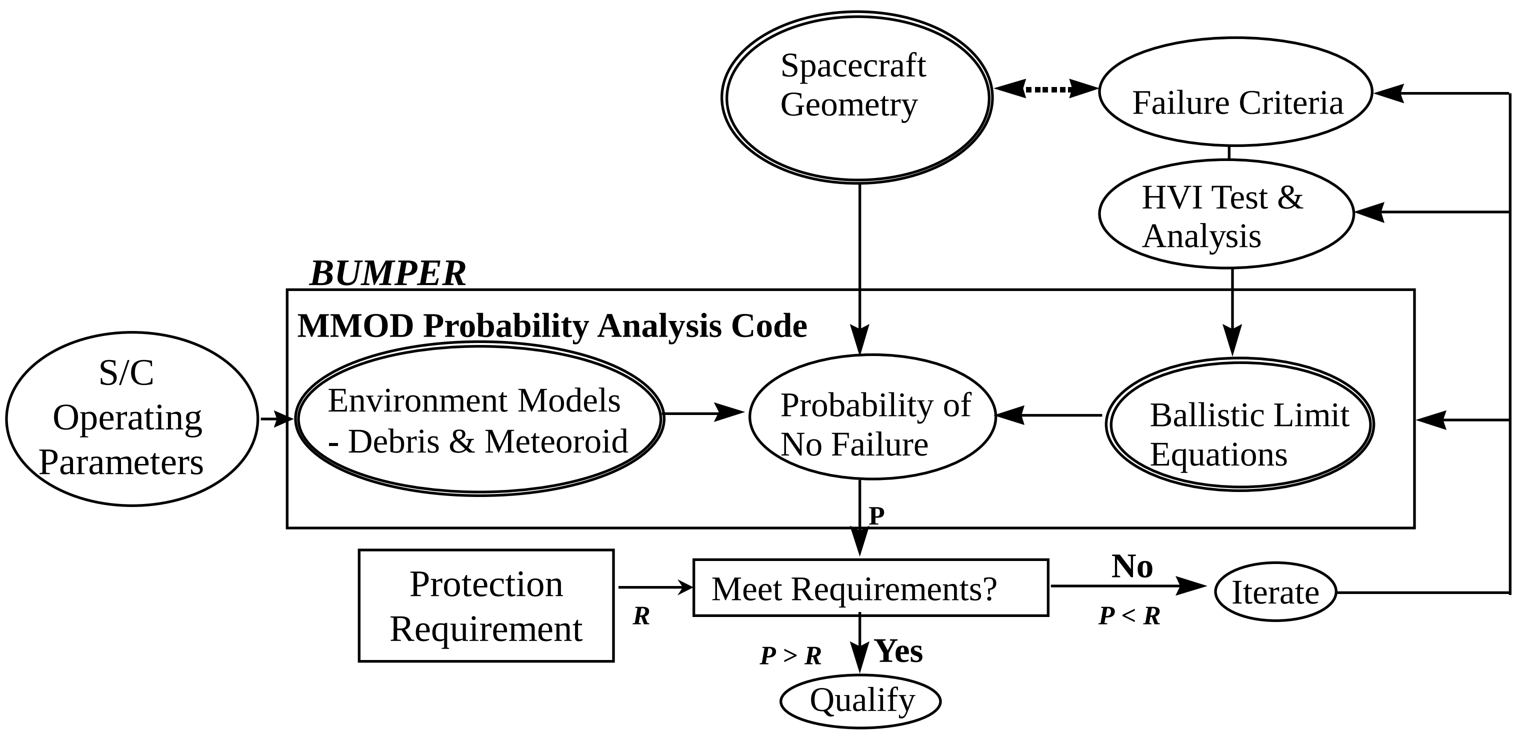


Surface Inspection Crawler assuming Electroadhesion:
(L) Emerging for deployment (R) Approaching Tile Damage

Backup Charts

Shielding Design and Verification Methodology

- Identify vulnerable spacecraft components/subsystems
- Assess HVI damage modes
- Determine failure criteria
- Perform HVI test/analysis to define “ballistic limits”
- Conduct meteoroid/debris probability analysis
- Compare MMOD analysis results with requirement
- Updates to design, operations, analysis, test, or failure criteria
- Update/Iterate as necessary to meet requirement

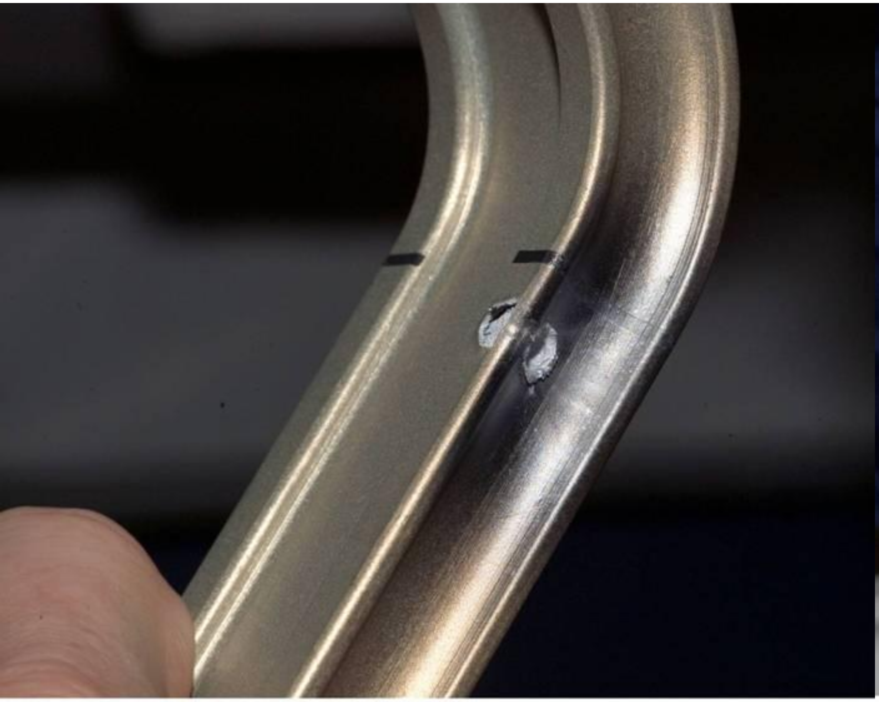


Window 13 impact damage

- Window 13 damage was sufficient to require an internal pressure cover to “safe” the window
  - Cover is opaque, which results in the window being non-usable while the cover is in place

EVA D-handle Tool

- A MMOD impact crater with detached spall found on an EVA tool (D-handle) during STS-123 (March 2008)
- D-handle stored externally on ISS Z1 Truss
- Damage repaired prior to use during STS-123 EVAs (edges filed and handle taped)



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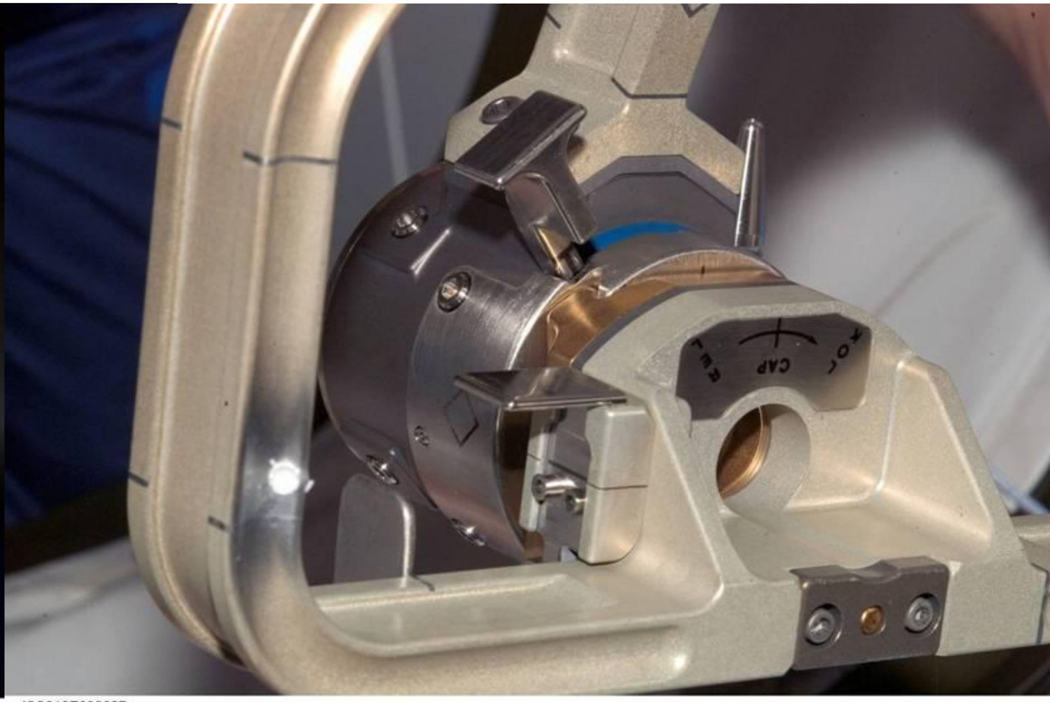

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Service Module solar array damage